A field study and computer modelling of groundwater flow in Ahamdy area, Kuwait

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A field study and computer modelling of groundwater flow in Ahamdy area, Kuwait

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Abstract

The present work addresses the impact of the infiltration rate and the heterogeneity of soil on the hydrodynamic conditions in unsaturated underground flow regimes. A two dimensional finite element model was adopted to simulate the groundwater flow in porous media, which represented the flow of contaminated water through Darcian flow regimes. The porous regions were assumed unsaturated and anisotropic with a constant porosity. The study aimed to demonstrate the influence of rainfall on the mobility of contaminated water in underground soil layers in terms of the infiltration rate. The developed model provides a tool to predict the concentration of contaminants in highly polluted lands.

In Kuwait, the Ahmadi area consists of three petroleum refineries (MAB, MAA, and SHU), which have been considered a potential source of underground water pollutants. A network of 45 monitoring wells has been established to determine the groundwater depth at different locations. The study is supported exclusively with field data collected from these monitoring wells to validate the model and show an accurate picture of the present work.

The outcome of this work is expected to show that the concentration of some solutes (agents) exceeds the local and international environmental guidelines for industrial site pollution.

Furthermore, the model can be used to adopt and implement a clear environmental policy to recommend a short- or long-term procedure to minimise the pollution of groundwater.

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Nomenclature

$P_{soil\text{-}water}$:	Soil-water partition coefficient;
g:	Acceleration due to gravity;
p:	Hydrostatic fluid pressure;
K:	Permeability of the porous medium;
Q:	Volumetric flow rate:
Re:	Reynolds number;
U:	Normalised velocity, x-direction:
V:	Normalised velocity, y-direction:
W:	Normalised velocity, z-direction:
P:	Normalised fluid pressure:
t:	Time variable:
C_{soil}:	Concentration of oil adsorbed to the soil;
C_{water}:	Concentration of oil dissolved in water;
u:	Fluid velocity;
ΔP:	Is the Pressure gradient operator;

Greek symbols:

ρ :	is fluid density
K:	is a tensor of permeability
ρ :	Fluid density
υ :	specific fluid velocity through porous medium
d:	is the representative gain diameter 30 % of passing size
μ:	is the dynamic viscosity

Subscripts:

p: Pressure;

v: Velocity

x: In x direction in Cartesian coordinates:

y: In y direction in Cartesian coordinates:

z: In z direction in Cartesian coordinates:

CHAPTER 1
INTRODUCTION

1.1 Water resources in Kuwait

The state of Kuwait has a total area of 17 850 km², located at the northern part of Arabian Gulf and characterised by a predominant year-round desert climate. The country shares the north and west border with the republic of Iraq and with the Kingdom of Saudi Arabia in the south and southwest. It overlooks the Arabian Gulf to the east. The landscape consists of gently undulating desert topography with a maximum altitude of approximately 300 m in the west that progressively declines eastward towards the Arabian Gulf. A system of shallow valleys and ephemeral streams dissects the Kuwaiti landscape. The arable area of Kuwait is characterised by a soil with a sandy texture, containing 85-90 percentage sand. It is very rare to find green lands and the nutritional elements needed by plants. Hard pans at different depths of the soil prevail and constrain the water permeability.

Kuwait has a desert climate in the summer and winter. Summer temperatures exceed 50 °C with frequent sandstorms from time to time. The winter is cold, with temperatures sometimes reaching below 4 °C. The rainy season starts from October to May. The annual rainfall is less than 100 mm over an area of approximately 100 km², whereas it varies between 120-and 330 mm in the remaining part. The average annual rainfall for the country is approximately 123 mm. recently, rainfall measurements have varied between 107 and 135 mm/year.

The total population is 2.695 million (year 2005), the population density is around 151inhabitants/km² but it varies according to region. The annual population growth for both Kuwaiti and non-Kuwait residents was estimated at 3%in 2005.The hot climate of Kuwait is not appropriate to the existence of any river systems in the country. There are no rivers or lakes across the country, but small wadis formed in the low depressions in the desert region, and large wadi depressions are sometimes formed during the rainy season. Although the underground formation contains groundwater resources, these reservoirs are considered limited under low measurements of infiltration rate due to the rare annual rainfall. Because of high evaporation rates and high deficit in soil moisture, only a small amount of the precipitation infiltrates into the groundwater resource. Groundwater inflow has been estimated at approximately 20 million m^3/year via lateral underflow from Saudi Arabia.

Two types of water can be found in these formations:

1- Fresh groundwater: This water contains less than 1,000 mg/l soluble salt and is not for farms or industries usage, but is considered a strategic freshwater reservoir for local demand. These freshwater reservoirs are formed due to high-intensity rainfall over a short period that enables continuous infiltration to the underlying groundwater.

2- Brackish groundwater: This water contains between 1,000 to 7,000 mg/l soluble salt and is a natural supply for agricultural and domestic purposes and as drinking water for animals. Thiswater is extended over Al Shaya, Al Qadeer, Al Solaybeia, Al Wafra and AlAbdali fields. The total capacity of these fields is approximately 545,200 m^3/day.

3-Saline groundwater: The salt content in this water is varied between 7,000 to 20,000 ppm, and it is therefore not appropriate for agricultural or domestic use, It may use in industrial purpose as a cooling media for some petrochemical plants and power stations.

To preserve these valuable water resources, only limited amounts of water is being supplied from the freshwater lenses and bottled for drinking purposes. These resources covering only 5% of Kuwait's drinking water demand. The main supply comes from desalinated seawater and brackish groundwater mixed with distilled water to lower the salinity (Fadlelmawla and Al-Otaibi 2005). The groundwater fields of Kuwait are shown in Figure 1-1. Wherein large amounts of brackish groundwater are being supplied for irrigation and domestic purposes from the fields located nearby farms area.

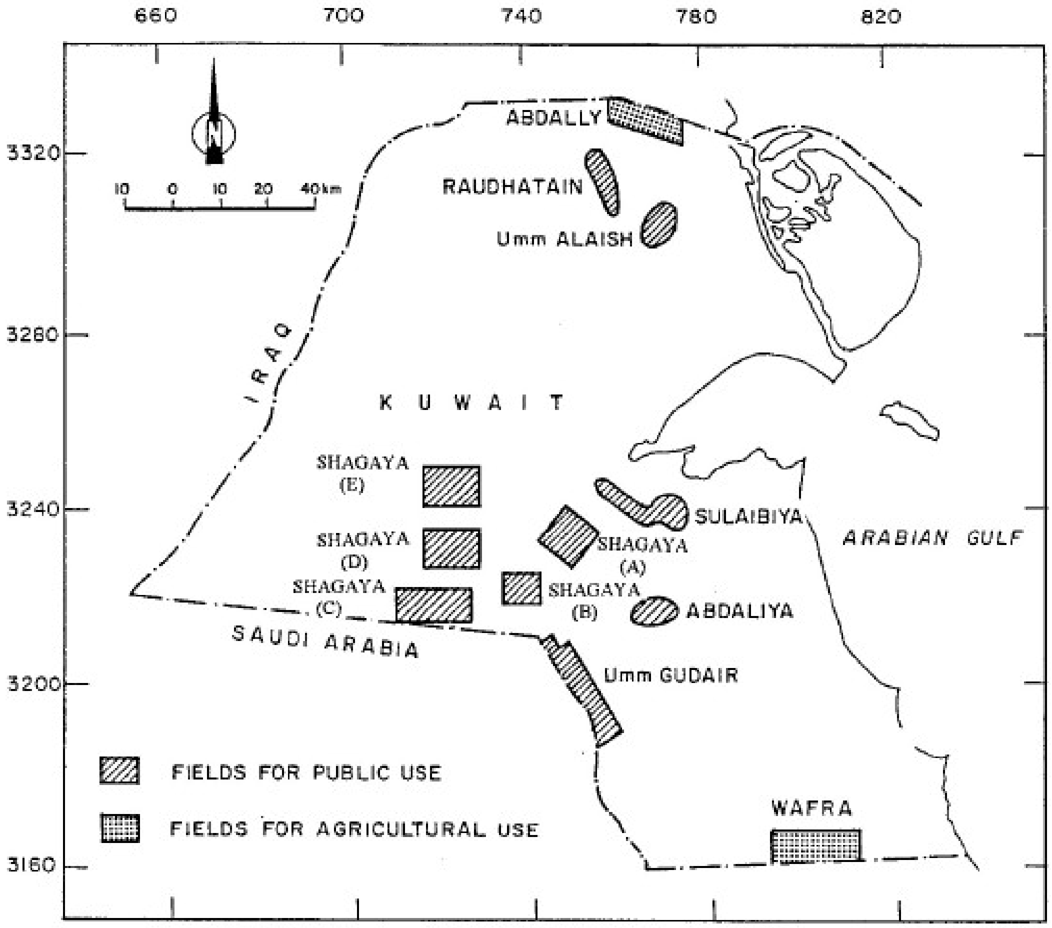

Figure 1-1: Kuwait groundwater

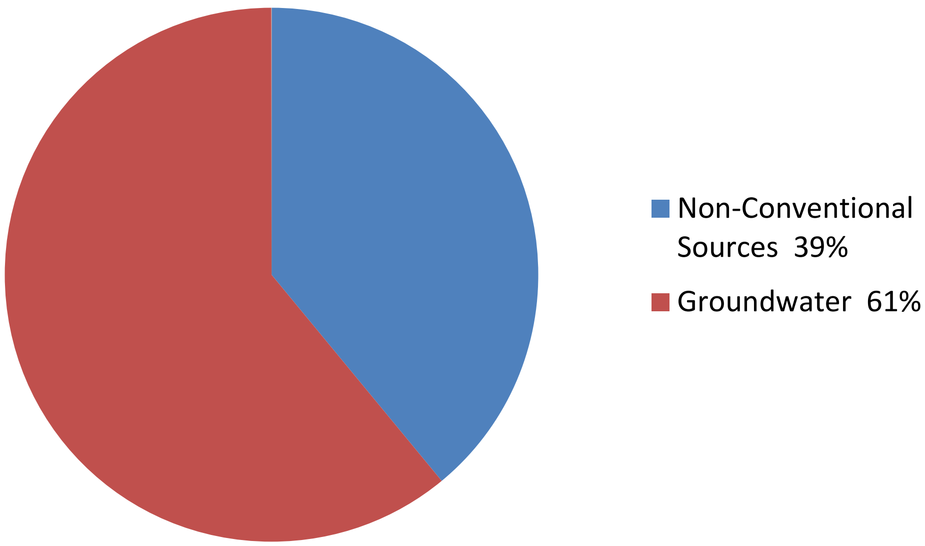

Figure 1-2 Kuwait Water Resources

In 2002, the total water consumption was approximately 913 million cubic metres, compared with 539 million cubic metres in 1993. The water consumption in Kuwait is considered the highest in the GUCCI countries. Fifty-four % of the water withdrawn was used for agriculture, 44 % for municipal purpose sand 2 % for industrial purposes Figure 1-3.

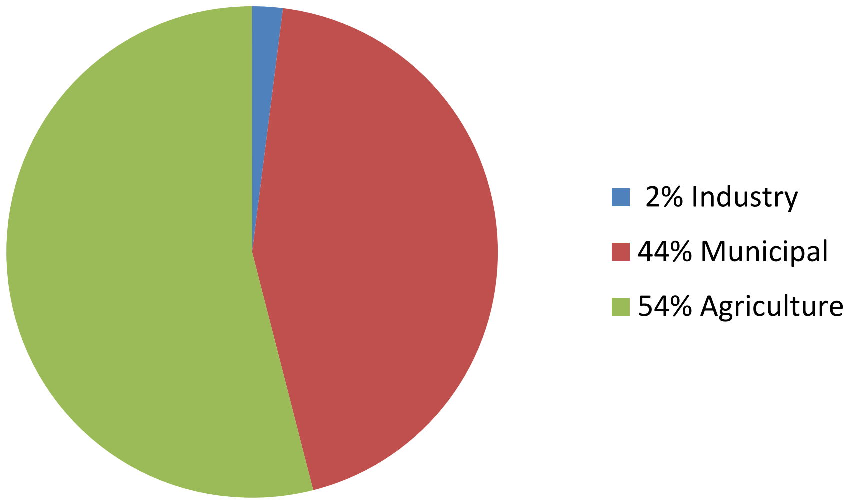

Figure 1-3 Water withdrawal by sector in 2002

Out of the 493 million cubic metres withdrawn, 80 % was for agriculture use, 9 % for landscape greening, and 11 % for public use. (This figure also includes some non-drinking for domestic uses).

Of the water withdrawn for agriculture purpose, 300 million cubic metres is brackish water in farm lands at the Al Wafra field in southern Kuwait and .66 million cubic metres comes from recycled wastewater effluent (50 % tertiary treatment and 50 %from advanced treatment). Fresh water withdrawal (Figure 1-4) amounts to 255 million m^3/year, which is equivalent to more than 12 times the annual groundwater inflow (20 million m^3). The Ministry of Electricity and Water MEW from the

Damman group aquifer pump the water used for daily life purposes through deep wells.

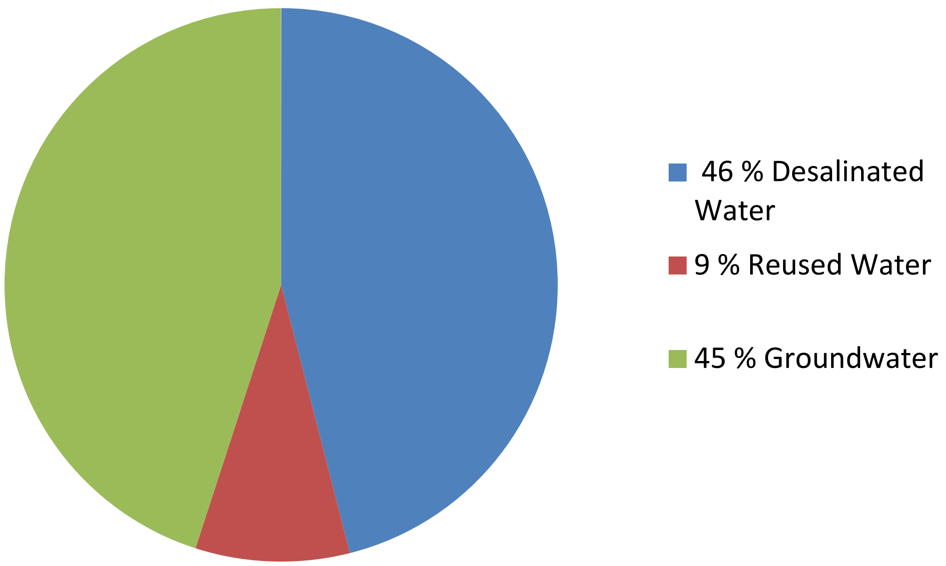

Figure 1-4Water Withdrawal by Source 2002

1.2 The aquifer system

Aquifers are geologic formations that can be defined as layers of sand, gravel, and rock in which sufficient quantities of water can be stored, move and supplied to a well. They are irregular in shape, near the surface, or very deep. There are two types of aquifers may exist in nature: confined and unconfined. Unconfined aquifers, generally located at nearest point to the surface, do not have layers of clay (or any other kind of impermeable geologic underground formations). The upper layer of groundwater within an unconfined aquifer is the water table. In most places, the water table is actually above the surface of the land. Groundwater that normally present in an unconfined aquifer (sometimes called a “water table aquifer”) is more susceptible to contaminants inflow from surface more than a confined aquifer because pollutants on the land surface can invade the unconfined aquifer during infiltration process.

Kuwait aquifer Group consists of Dibdibba, Lower Fars, and Ghar formations. The Dibdibba formation, consisting of ungraded series of sands and gravel with subordinate interactions layers of sandy clay, sandstone conglomerates, and siltstones. This formation also contains sufficient amount of freshwater quantities.

The underlying lower Fars formation consists of fine sediments, conglomeratic sandstones, shale, and thin fossil ferrous limestone. The Ghar formation primarily consists of marine and terrestrial sands, silts, and gravel. The sands are generally coarse and unconsolidated. Kuwait aquifer system is formed from two groups known as the Hasa and Kuwait group. The Hasa group consists of limestone, dolomite, anhydrite, and clays and comprises three formation units: the Ummer Radhuma from the Palaeocene to the Middle Eocene, the Rus in the Lower Eocene, and the Damman in the Middle Eocene.

The Kuwait group consists of fluvial sediments of sand and gravel, calcareous sand, and sandstone with some clays, gypsums, limestone, and marls. It comprises three formation units, known as the Ghar in the Miocene, Fars in the Pliocene, and Dibdibba in the Pleistocene.

Over the natural course of hydrological events, the groundwater salinity increases gradually in the lateral flow direction towards the discharge area and becomes relatively brackish before reaching the territory of the state of Kuwait, with TDS between 2500 and 5000 ppm. The main source of groundwater in Kuwait is the accumulated rainwater and the Jurassic water, which exists in the underground rock formation and originated thousands years ago. Some precipitation from the surface water is known to infiltrate the ground and break down until it reaches a depth in which all fractures, crevices, and pore spaces are saturated with water. This saturated zone forms the groundwater reservoir. The upper portion of saturation zone is the water table. In other words, the water table is the first formation found of groundwater. The formation above the water table is considered as unsaturated zone. The distance between the water table and the ground surface depends on the location with respect to sea level as well.

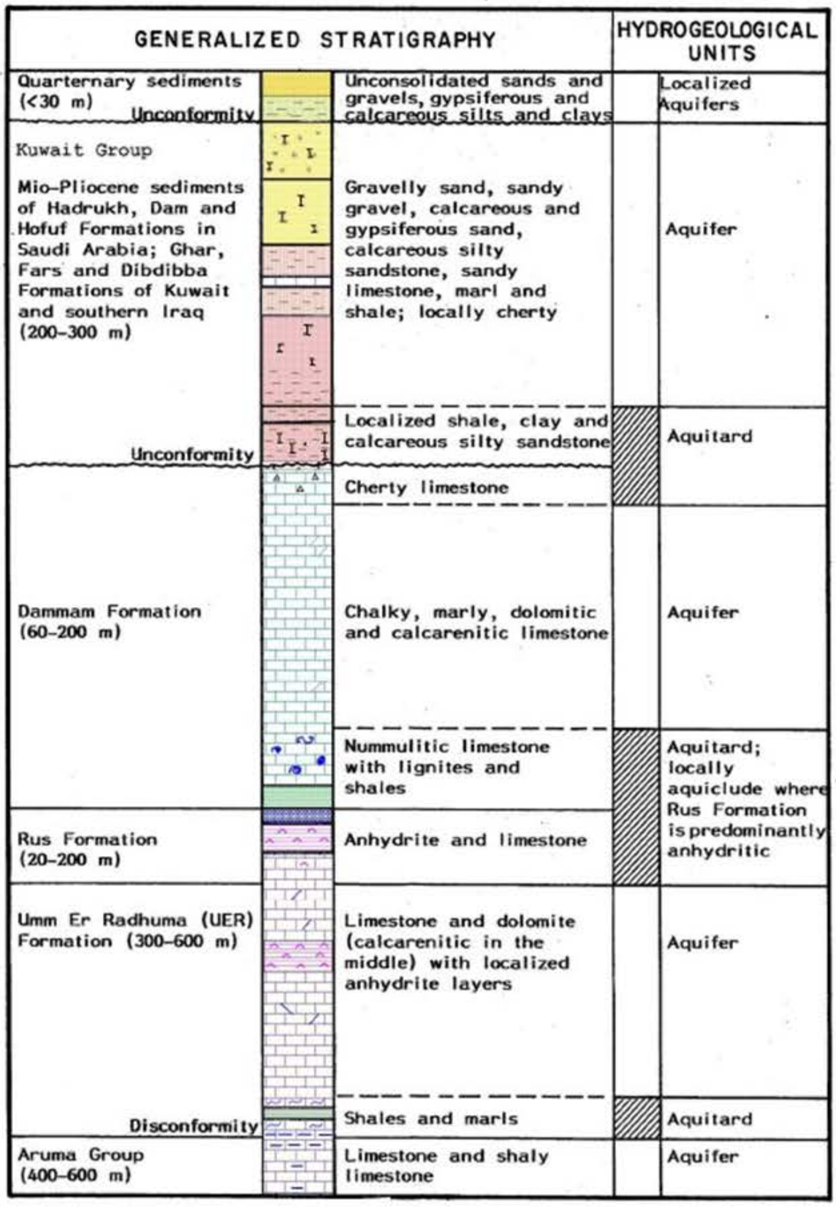

Figure 1-5: Hydrostratigraphy of Kuwait (Source: Mukhopadlyay et al., 1996,p.277)

1.3 Environment and Pollution

The unique natural freshwater resource in Kuwait found as lenses floating on the saline groundwater in the northern part of the country near the oil fields. Rainwater is the only means of recharging this limited groundwater resource, which is dominated by the infiltration rates. This groundwater is utilized as bottled drinking water, and the fresh groundwater aquifer is considered a strategic drinking water reserve for Kuwait.

In Kuwait, as in other countries of the world, the main concerns regarding water recycling and reuse are:

- The effective wastewater treatment to comply with water quality for the intended use.
- To reserve the public health.
- Satisfy public acceptance

Several public health concerns are encountered if recycled water is used to recharge groundwater, irrigate green residential spaces with high public contact. While the potable reuse of treated wastewater is extremely prohibited, groundwater recharge with advanced method of wastewater treatment is a standing option. Per our future plans, we show in this study that water-conserving efforts in Kuwait should focus on this type of replenishment to maintain stable and rechargeable amounts of groundwater with sufficiently low salinity.

1.4 Oil refinery operations and the environmental impact

1.4.1 Petroleum refinery definition

Petroleum refinery is organised arrangement of manufacturing process units to convert crude oil to its valuable pure hydrocarbon products by physical and chemical changes. These products include fuel gas, LPG, gasoline, diesel, lubricating oil, and fuel oil. Petroleum is a complex mixture of organic liquids called crude oil and natural gas. Some of the technologies used in the refinery require a cooling sea water system to enhance the productivity and quality of the products. Potential sources of water contamination include cooling water, spilled water, and water that are actually used as part of cooling processes. Effluent liquids from a refinery may contain pollutants and hydrocarbons. Fluids used in the process, such as hydrocarbons, should be returned through a network of collection pipes system and then reprocessed through the distillation units. Wastes that cannot be rerouted, can be recycled to manufacturers, disposed of in approved facilities, or chemically treated on-site to form inert materials, which can be disposed of in a landfill within the refinery.

The Kuwait refineries are considered a major source of pollution and harmful wastes. Unexpected shutdown, poor maintenance, faulty equipment, loss of environmental controls, damage due to combat activities, and leakage from the tank area (tank farm), etc., may significantly affect local refineries and result in less than optimal system performance. If the refinery is poorly operated or is compromised, the release of pollutants to the local environment may result in high amounts of pollutants.

Petroleum refining techniques include fractionation, thermal cracking, hydro cracking, reforming, isomerisation, hydro treating, combination/blending processes, and transport. The refining industry provide various products widely used in day to day life, including petroleum gas, kerosene, and diesel fuel, motor oil, asphalt, and waxes. Because of changes in oil prices due to the environmental impact of the quality of fuel gas used in the refinery process system, the industry is shifting towards alternate fuel use and increasingly focusing on conservation. This trend has been found due to certain requirements on the facilities to produce cleaner fuels to comply with new state rules and regulations toward clean air and water.

1.4.2 Processes involved in refining crude oil

Understanding different processes in Kuwait oil refineries will guide our knowledge of the pollutants in question. The operations of an oil refinery involve a series of processes include distillation, separation, blending, treating and unifying products. The five major processes are as follows:

• ***Distillation processes***: this process involves separating the different grade of hydrocarbon compounds from crude oil according to their boiling point differences. Crude oil consists of a wide range of components that can generate gasoline, diesel, oils, and waxes. Kuwait KNPC refineries commonly use atmospheric and vacuum towers called CDUs (Crude Distillation Units) to distil crude oil. Kuwait refineries have five CDUs with a total throughput of 950 MBPD. These fractions usually require further processing to generate final products to be brought to market.

• ***<u>Conversion processes</u>***: This process include Cracking, reforming, coking, and isomerisation. conversion processes used in the three refineries to break long chain of hydrocarbon compound into smaller by heating or using catalysts (hydrocracking or thermal cracking)in the presence of hydrogen. These processes allow KNPC to break down the heavy oil fractions into lighter fuel to increase up the profitability, valuable products, such as gasoline, diesel fuels, or other products on demand.

• ***<u>Treating Process</u>*****:** The KNPC treatment processes usually employ hydrogen gas to extract undesirable agent and impurities, such as sulphur, nitrogen, and heavy metals, from the products. This separation involves processes such as hydro treating, desulphurisation, acid gas removal, and sweetening. Some of the KNPC treatment units, such as the ARDS (Mina Abdullah refinery), Amine unit (Mina Ahmadi refinery), sulphur recovery unit (Mina Shuaiba refinery), and Naphtha unifiner unit, are typical examples of treatment units.

• ***<u>Blending processes:</u>*** KNPC refineries is applying blending processes to produce commercial mixtures to the global market that meet the petroleum specification to produce a desired final product. This process is usually designed to enhance the octane number. The common blending process is to combine different mixtures of hydrocarbon to produce lubricants, asphalt, or gasoline with different octane numbers.

• **<u>Auxiliary processes:</u>** KNPC refineries also have other units that are vital to their operation to supply the major processes with stripping steam, waste treatment, and other utility services. Supplies from these facilities are recycled into the system and used in other processes within the refinery for chilling or stripping (heating or cooling media). These processes are also important because they minimise water and air pollution. Examples of these units are utility boilers, wastewater treatment (WWT) units, and cooling towers. The wastewater or drainage from the slope of the downstream unit may still contain some impurities.

1.4.3 Classification of Hydrocarbons

The term petroleum is a Latin name derived from words *petra* for rock and *oleum* for oil. Currently, petroleum is known as any hydrocarbon mixture of natural gas, condensate, and crude oil. Crude is defined as a heterogeneous liquid mixture that consists of hydrocarbons compound that consists of hydrogen and carbon atoms in a ratio of approximately 1.85 hydrogen atoms to 1 carbon atom. Minor constituents, typically comprising less than 3% of the total volume, include sulphur, nitrogen, and oxygen. Trace constituents, typically comprising less than 1% of the entire volume. The composition may vary with the location and age of an oil field and may even depend on the depth of an individual well. Crude oil consists of a mixture of hydrocarbons of varying molecular weight and on average contains approximately 84.5% carbon, 13% hydrogen, 1.5% sulphur, 0.5% nitrogen, and 0.5% oxygen.

The study of hydrocarbon pollution of groundwater requires an understanding of the properties of hydrocarbons and, in particular, petroleum hydrocarbons. Hydrocarbons are divided into two categories:

(1) Aliphatic hydrocarbons, which consist of long chains of carbon atoms. These atoms are joined by single bonds (alkenes), double bonds (alkenes), and triple bonds (alkynes).

(2) Aromatic hydrocarbon, which contain benzene rings. Benzene rings consist of six carbon atoms joined in a ring structure with alternating single and double bonds.

Alkanes are saturated hydrocarbons because they contain single bonds. These are also known as paraffin, e.g., methane, ethane, and propane. Alkanes can also have a cyclic structure; these alkanes are known as cycloalkanes, cycloparaffins, or naphthenes. Alkenes have carbon-carbon double bonds and are unsaturated hydrocarbons. These hydrocarbons are also known as olefins, e.g., ethane (or ethylene) and 1-butane.

Aromatic hydrocarbons are based on benzene rings. When a single functional group such as CH_3 is attached to the benzene ring, it is known as methylbenzene (or toluene). Two or more benzene rings may be joined together. The simplest polycyclic aromatic hydrocarbon (PAH) is naphthalene. PAHs are found in the heavy fraction of the petroleum distillate, asphalt, and coal tar. If benzene rings are chlorinated, they are known as polychlorinated biphenyls or PCBs. These molecules are quite resistant to chemical, thermal, or biological degradation and tend to persist in the environment. Typical crude oil might consist of approximately 25% alkanes (paraffins), 50% cycloalkanes (naphthalenes), 17% aromatic hydrocarbons, including polycyclic aromatic hydrocarbons, and 8% asphaltics, which are molecules of very high molecular weight with more than 40 carbon atoms.

1.4.4 Types of petroleum pollutants in the Ahmadi area

Pollutants from the KNPC Refineries can be classified by the surrounding media that they affect. Three types of pollution exist in the local Ahmadi area: air pollution, water pollution, and soil pollution.

Air pollution: KNPC refineries are the main source of toxic air pollutants, such as BTEX compounds (benzene, toluene, ethylbenzene, and xylene). They are also a major source of critical air pollutants: particulate matter (PM), nitrogen oxides (NOx), carbon monoxide (CO), hydrogen sulphide (H_2S), and sulphur dioxide (SO_2). These refineries also release some hydrocarbons, such as natural gas (methane). Some of the released chemicals are detected or suspected carcinogens that are responsible for developmental and reproductive problems. Along with the possible health concern from exposure to these chemicals, these pollutants may cause worry and fear among the people of surrounding communities.

Other emissions may can come from various sources within Ahamdy Area , including equipment leaks (from the storage tank or API gravity separator), high-temperature combustion processes as flue gas coming from power generation, the heating of stripping steam and process units, and the transfer of products. Large quantities of pollutants are potentially emitted into the surrounding environment over the year through normal emissions. The combination of volatile hydrocarbons and oxides of nitrogen also contributes to ozone layer, affecting the most significant air pollution problems in the world.

• ***Water pollution:*** KNPC Refineries are deemed potential major sources of groundwater and surface water contamination. Some of Kuwait's oil wells use deep-injection technology to dispose of wastewater generated inside the plants, and the majority of these wastes eventually reach aquifers and groundwater formation. The effluents of wastewater from the refineries may be highly contaminated given the number of sources; water can be exposed to impurities during the refinery cooling process. This contaminated water may be from desalting, cooling towers, cooling water, distillation, or hydro cracking.

Contaminated water may also contain oil residue and any other pollutant wastes. It is recycled through different production units during the refining process and undergoes through several treatment processes, including a wastewater treatment plant, before being released into natural water system. These discharge guidelines limit the amounts of sulphides, ammonia, suspended solids, and other compounds that could be present in the wastewater.

• ***Soil pollution:*** contamination of soils due to KNPC refining processes generally has less significant problem when compared with the contamination of air and water. Spills are possible on the refinery property during normal operation, which may need to be cleaned up. Microbial degradation can be used to clean the soil. Many residuals are formed within refining processes, and some of them are recycled back into the system to minimize the losses in feedstock and to enhance the yield. Other residuals are accumulated and disposed of in landfills, or they may be recovered by other facilities. Soil contamination from spent catalysts, solid wastes, coke dust, tank bottoms, and sludge from the receiver sludge catcher can occur from leaks and accidents or poor operation.

1.5 Problem statement

1.5.1 General Background.

In general, groundwater quality and quantity is a point of concern in Kuwait due to the continuous pumping. At the south of the country Al Wafra, 50 percent of the wells pumped water with a measured salt content higher than 7500 ppm in 1989, increasing up to 75 percent and 85 percent in the years 1997 and 2002 respectively. At the north of the country Al Abdali in the north, these measures were estimated at 55, 75 and 90 percent respectively. Kuwait dependent on the desalinated water from the gulf sea for the major use of the entire country. The first desalinating plant was built at Al Ahmadi port in 1951, with total capacity of 364 m3/day. The production capacity increased progressively until it reached 1.1 million m3/day, while maximum consumption reached 0.9 million m3/day in the summer of 1995 (PAAFR, 2006). In 2002, the annual quantity of desalinated water produced was 420 million m3 (FAO, 2005). The main challenge with seawater distillation due to its highly cost of the multi-stage flash (MSF) operational process and capital cost. The cost of the thermal process is very dependent on the rate of energy consumption for operating the system, which can account for as much as about 50 percent of the water unit cost, thus cost wise of fuel is linked to global price of fuel.

Most of the population area is connected to a central sewerage network. This was considered as important potential for treated wastewater reuse that can contribute to overcome the water shortage problem. However, various reasons affect the quality and quantity of sanitary sewage from time to time. Due to the multiple cycle of treatment, process and piping system that might be exposed to open land and process upset conditions. Qualitative and quantitative monitoring of the system and of the effluent from post treating process to the final use for various purpose is essential to prevent the potential hazards associated with wastewater reuse. The sewerage system collects over 90 percent of the raw domestic and some industrial wastewater (220 million m3/yr.), in addition to part of the storm water runoff in the residential areas which are connected to the sewerage system. Wastewater treatment has two main purposes: i) to protect public health and the environment; ii) to use treated wastewater for irrigation to compensate for the water deficit. In 2002, the wastewater treated produced 152 million m3 of which 78 million m3 was reused, which means an increase of 48 and 50 percent respectively compared to 1994. In 2005 the total amount of treated sewage water was estimated at 250 million m3/year .Treatment plants are gradually being upgraded to advanced levels of treatment with the first plant (Al Solaybeia) planned to begin operating by the end of 2004.

The main source of groundwater in Kuwait is the accumulated rainwater and the Jurassic water, which was trapped in the underground rock formation thousands years ago. The water cycle includes precipitation from the surface water, which infiltrates the ground and breaks down until it reaches a depth at which all the fractures, crevices, and pore spaces are saturated with water. This saturated zone is a groundwater reservoir known as an “aquifer”. The upper surface of the zone of saturation is the water table. In other words, the water table is the first formation of groundwater. The region above the water table is called the unsaturated zone. The rainy season extends from October to May. The annual rainfall over an area of approximately 100 km is less than 100 mm, whereas it is between 100 and 300 mm in the remaining part. The average annual rainfall for the whole country is approximately 121 mm. recently, rainfall measurements have reduced to be between 106 and 134 mm/year.

Most of the water withdrawn from the underground formation is for productive agriculture, 300 million cubic metres is brackish water from private farms in the Al Wafra region of southern Kuwait, and .66 million cubic metres comes from treated wastewater effluent (50 % tertiary treatment and 50 % more advanced treatment). Fresh groundwater withdrawal amounts to 255 million m^3/year, leading to an extraction of more than 12 times the annual groundwater inflow (20 million cubic metres). The Ministry of Electricity and Water (MEW) pump the water from the Damman group aquifer for daily life purposes through deep wells.

For the aforementioned reasons, the Kuwaiti government began to implement a preventative policy and had developed guidelines to preserve the natural groundwater resources from pollution and irregularly high consumption through the K-EPA (the Kuwait Environment Public Authority). As a part of these national efforts, this study aimed to focus on the impact of the Kuwait Refineries on the groundwater level and quality in the Al-Ahmadi industrial area.

1.5.2 Work plan and objectives

The present work aimed to study the groundwater recharge rate and its influence on the mobility of some contaminant through the underground porous formation and the impact of the infiltration rate and heterogeneity of the soil on the hydrodynamic conditions in unsaturated underground domains. A two-dimensional finite element model will be used to simulate the underground flow in porous media and represent the flow of contaminated water through Darcian flow regimes. The porous regions above the water table is assumed unsaturated while the region below the water table is considered as saturated zone were assumed to be unsaturated and anisotropic with a constant porosity. This study showed the influence of rainfall on the mobility of contaminated water in underground soil layers in terms of the infiltration rate. The developed model provides a convenient tool to predict the concentration of contaminants in highly polluted lands.

In Kuwait, the Ahmadi area consists of three petroleum refineries (MAB, MAA, and SHU), which have been considered to be potential sources of underground water pollutants. A network of 45 monitoring wells was established to determine the groundwater depth at different locations. The study was exclusively supported with field data collected from these monitoring wells to validate the model and show a real picture of the present work.

The outcome of this work is expected to show that some solute (agent) concentrations exceed the local and international environmental guidelines for industrial site pollution. Furthermore, the model can be used to adopt and implement a clear environmental policy to recommend a short-term or long-term procedure to minimise groundwater pollution.

To achieve these goals, the study shall include but not be limited to the following:

- Identification of the extent of potential contamination at the company refinery sites and its surrounding areas,
- Identification of optimal management procedures to avoid potential short- and long-term environmental liability,
- Determination of the source, extent, and distribution of groundwater contamination with petroleum products beneath the refinery and its surrounding sites,
- Assessment of monitoring well locations and examination of their accuracy,
- Development of a plan to remediate the aquifer and prevent further pollution in the future and
- Recommendation of preventive measures to stop further deterioration of groundwater at the surrounding areas of company refinery sites.

1.5.3 Site location and conditions

In 1960, the Kuwaiti government established the KNPC. In 1962, the Kuwaiti Oil Company (KOC) relinquished 60% of the areas included in its concession to KNPC. KNPC handles oil refining, gas liquefaction, and distribution of petroleum goods within the local market. KOC started refining operations with the Mina Al-Ahmadi Refinery in 1949. The refinery was initially built in 1949, with a refining capacity of 25,000 bpd to fulfil the local market needs for gasoline, kerosene, and diesel. The refinery was handed over to KNPC in 1980. The AI-Shuaiba Refinery was builtin 1966 and was the first refinery in the region to be built by a national company. The Mina Abdullah refinery was built in 1958 by the American Independent Oil Company (AMINOIL) and was later passed to the State of Kuwait in 1975 and transferred to KNPC in 1978. By 1989, the KNPC had three modern refineries, including the Mina Al-Ahmadi, Mina Abdullah, and Al-Shuaiba sites.

The study area is located in the south-eastern part of Kuwait and covers the three Kuwaiti refinery sites and their surrounding area (Figure 3-1). It has a surface area of approximately 68 km^2. The names of the three refineries, from north to south, are as follows: the Mina Al-Ahmadi Refinery, Al-Shuaiba Refinery, and Mina Abdullah Refinery. The surrounding area to the west of the three refineries is the Mina Abdullah Industrial Area and is an open desert area. Other industrial units are situated between the three refineries: the Kuwait Petrochemical Industrial Company (PIC), the Al-Shuaiba Southern Desalination Plant, the Equate Petrochemical Company, and the Kuwait Cement Company. Two seaports are to the east of the study area: the Al-Shuaiba Commercial Port and the Al-Ahmadi Port, in which crude oil and its products are loaded. An open space occupies the area between the Al-Ahmadi and Al-Shuaiba refinery, and the same is true for the area between the Al-Shuaiba and EQUATE Petrochemical plant. The National Industries company quarry is located approximately 4.0 km to the west of the Al-Shuaiba Refinery.

The nearest population centres to the Mina Al-Ahmadi refinery are the Al-Fahaheel suburb, the Ali Al-Salem suburb, and Al-Ahmadi City, which is located approximately 2.3 km to the northwest of the Al-Ahmadi refinery. The Al-Ahmadi Ridge is approximately 120 m above sea level. The Ali Al-Salem suburb is located to the southwest of the Mina Abdullah refinery.

Figure 1-6 Al-Ahmadi Area

Kuwaiti National Company (KNPC) operates the three refineries. The company is aspiring to preserve the environmental integrity of Kuwait and wants to follow the rules and regulations in place for the industry to ensure the environmental wellbeing of the country's natural resources and its people. In view of these aims, KNPC has installed a groundwater-monitoring network by drilling 47 monitoring and testing wells across the three refinery areas. The monitoring system at the Mina Abdullah refinery includes 18 wells, the monitoring system at the Mina Al-Ahmadi refinery consists of 14 wells, the monitoring system at the Al Shuaiba Refinery features 13 wells, and the monitoring system outside the refinery area consists of two monitoring wells. The wells were a mixture of multilevel wells specifically designed for dual-purpose production and the sampling of contaminants at selected depths and observation wells to determine the depth of the groundwater.

CHAPTER 2
Literature Survey

2.1 Porous Media and aquifer

Fluid flow and mass transport phenomena can be recognized in a large number of environmental problems such as saltwater seepage in coastal aquifers, It can also be seen in industrial processes such as drying processes or particulate industrial materials. For these problems, Modeling variable density flow problems under heterogeneous porous media conditions has been constructed (A. Younes M. Konz .M. Fahs, 2011). The DASPK solver for temporal resolution is combined with advanced spatial discretization system to improve the computational efficiency. The spatial discretization is based on a combination of Mixed Finite Element (MFE), Discontinuous Galerkin (DG) and Multipoint Flux Approximation methods (MPFA). The obtained non-linear ODE/DAE system is solved with the Method of Lines (MOL) using the DASPK time solver. DASPK uses the preconditioned Krylov iterative method to solve linear systems arising at each time step. Precise laboratory-scale 2D experiments were conducted in a heterogeneously packed porous medium flow tank and the measured concentration contour lines are used to evaluate the numerical model. Simulations show the high efficiency and accuracy of the code.

In low-gradient systems, such as coastal plains, perturbations in the groundwater flow-field may be caused by discontinuities in the aquifer structure or by water withdrawals; the system response is closely tied to the vertical structure of its aquifers and aquitards. A systematic change in sediment thickness may arise, for example in a depositional marine environment where there are cone-shaped bedrock extrusions. An analytical model of this setting can be used to test its sensitivity to hydraulic conductivity and boundary fluxes.

Also the case of the presence of moisture flow in porous media are an important phenomenon in reservoirs recovery, environmental protection (chemical and nuclear contamination) and engineering structures (slopes, dams and surface storage reservoirs, underground Structures and buildings). Due to its importance, many models have been used to study moisture flow in fractured porous and/or permeable media. The models differ mostly in their assumptions of the interaction between the porous matrix and the fracture.

Water uptake in fractured brick samples can be monitored by using X-ray radiography. This technique can measure both the moisture profiles in the matrix and the height of the waterfront in the fracture. It was found that the waterfront in the fracture could quickly reach the opposite side of the specimen, resulting in an extra water source for the surrounding matrix over the total height of the sample. To simulate the experiments, a numerical model for unsaturated moisture transport in fractured porous media is developed by (S. Roels , K. Vandersteen, J. Carmeliet,2002). The model combines a discrete fracture model for moisture flow in a variable aperture fracture with a finite element model for unsaturated flow in the porous matrix. The numerical results of height of rise in the fracture as well as of moisture profiles in the matrix show to be in good agreement with the measurements.

heat and mass transfer from a curved surface has attracted a great deal of attention owing frequent applications of curved heat conducting surfaces. For examples the flow over a horizontal cylinder is of considerable significance due to the relevance of the cylindrical geometry to heat rejection systems, nuclear reactors, heating elements, temperature control of a catalytic bed, pipes conveying hot fluid in every generation system etc. Further the spreading of chemical contaminants through-saturated soil and extraction of geothermal energy (I.A. Hassanien Z.Z. Rashed ,2010) studied the effects of variable viscosity and thermal conductivity on coupled heat and mass transfer by free convection through a permeable horizontal cylinder embedded in porous media using Ergun mode. The fluid viscosity and thermal conductivity are assumed to be a linear function of temperature while the mass diffusion is assumed to vary as linear function of concentration. The surface of the horizontal cylinder is maintained at a uniform wall temperature and a uniform wall concentration. The transformed governing equations are obtained and solved by using the finite difference method. Numerical modeling resulted for dimensionless temperature and concentration profiles are presented for various values of parameters namely, Ergun number, transpiration parameter, Rayleigh and Lewis numbers and buoyancy ratio parameter.

Multiphase multi-component models for the simulation of flow and transport processes in the subsurface are used widely in various technical application fields. It characteristic of such compositional models that they consider the flow of more than one fluid phase (e.g. water, oil, gas, alcohol) and the transport of components in the fluid phases. Many multiphase and multi-component processes are strongly affected by non-isothermal effects, in particular when processes such as evaporation/condensation play a dominant role. Since the 1970s, numerical models have been developed in the petroleum industries.(H. Class , R. Helmig, P. Bastian, 2002) have shown the Modeling of non-isothermal multiphase multi-component flow and transport processes in the subsurface which requires the consideration of the transfer of mass and energy between the phases in addition to different type and features of flow processes such as advection and diffusion. They had developed a multidimensional numerical simulator, in which new efficient solution techniques were implemented. The description of the physical and thermo dynamical state yields a system of four strongly coupled partial differential equations. The set of phases present in the porous medium is variable in space and time. In order to consider this. They have adopted an algorithm that allows an adaptive switching of the primary variables according to each phase state. In addition, by applying a Newton algorithm for the linearization of the equations. For the solution of the arising linear equations, a multi grid method has been extended and adapted to the problem of variable phase states.

The most common governing equations used to describe the fluid flow in free zone and porous medium are Stokes and Darcy and the Computational modeling of coupled Stokes and Darcy flows has been actively considered and investigated in recent years due its many applications, including interaction between surface and subsurface flows, industrial filtration, fuel cells, and blood flows. (Pu Song, Changqing Wang, Ivan Yotov, 2013) considered a multi domain formulation, where the simulation domain is decomposed into a union of non-overlapping subdomains of either Stokes or Darcy type. The subdomains are discretized by appropriate stable finite elements on a fine scale, allowing the grids to be non-matching across interfaces. Coarse scale mortar finite elements are used to impose weakly continuity conditions. A non-overlapping domain decomposition method is developed for coupled Stokes-Darcy flows in irregular domains. The Stokes region is discretized by standard Stokes finite elements while the Darcy region is discretized by the multipoint flux mixed finite element method. The subdomain grids may not match on the interfaces and mortar finite elements are employed to impose weakly interface continuity conditions. The interfaces can be curved and matching conditions are imposed via appropriate mappings from physical grids to reference grids with flat interfaces. The global problem is reduced to a mortar interface problem, which is solved by the conjugate gradient method. Each iteration involves solving subdomain problems of either Stokes or Darcy type, which is done in parallel. Computational experiments are presented to illustrate the convergence of the discretization and the condition number of the interface operator.

Groundwater flows play a key role in the recharge of aquifers, the transport of solutes through subsurface systems or the control of surface runoff. Predicting these processes requires the use of groundwater models with their applicability directly linked to their accuracy and computational efficiency. A good understanding of subsurface water dynamics is essential in many hydrological, environmental and engineering applications.(De MAET T., HANERT E, 2014.) have presented a new method to model water dynamics in saturated porous media. This model based on a fully-explicit discontinuous-Galerkin formulation of the 3D Richards equation, which demonstrate a perfect scaling on parallel architectures. The adapted jump penalty term for the discontinuous-Galerkin scheme and of a slope limiter algorithm to produce oscillation-free exactly conservative solutions. It was shown that such an approach is particularly well suited to infiltration fronts.

Aquifers are very vulnerable sources of groundwater, which are largely used as drinkable and industrial water, especially since the aquifers are now being seriously threatened by increasing contamination. Therefore, a case study has been established for Karst aquifers for assessing groundwater risk and controlling groundwater pollution. One of the most popular models is so-called coupled continuum pipe-flow/Darcy (CCPF) model in which the conduits embedded in the continuum matrix are simplified into a network of one-dimensional pipes.(Wei Liu , Zhifeng Wang, Jin Li. 2014), has presented a Numerical method for a coupled continuum pipe-flow/Darcy model describing flow in porous media with an embedded conduit pipe . Finite element method is applied to solve the Darcy equation on porous media and finite element on regular mesh is used to solve the pipe-flow equation on conduit region. The existence and uniqueness of the approximation solution are considered. Two decoupling method are given to solve the resulting coupled system of equations. Optimal error estimates are obtained independent of the regularity condition on the mesh. Numerical examples show the efficiency of the given method. With the same number of nodal-points, the results on anisotropic mesh are much better than the same element on regular mesh.

(Mazda Kompanizare , Jonathan S. Price,2014), has developed an analytical solution to predict steady radially-symmetric percolation rates from an aquifer underlain by a variable thickness aquitard. The solutions consider an aquitard with constant thickness and with radial-symmetrically increasing thickness outward from the center. The solution was used to predict the percolation rate from a peat layer around a bedrock outcrop in the James Bay Lowland near the De Beers Victor diamond mine. In this case, the marine sediment layer limited the direct connection between the peat layer and the bedrock as an aquitard. The zero order solution with constant marine sediment thickness showed the best fit to the steady state water level data of June 2012. It was found that the enhanced recharge around bioherms (i.e., at rates greater than the regional average of 0.7 mm/day) will only occur in marine sediments less than 4.3 m thick, for extreme depressurization of 30 m

Another challenge of water requirement that is irrigation will escalate in future to meet the food demand of burgeoning population growth in the world. This necessitates the use of appropriate agricultural water management practices to enhance the irrigation efficiency and crop productivity under both poor and good quality water supply situations. Increasing demand of water by the agricultural sector and the need for enhancing the water use efficiency for sustainable production is reported by several researchers.

Crop modeling has played an important role in formulating agricultural policies and measures to reduce yield losses. (P. Kumar, A. Sarangi, D.K. Singh, S.S. Parihar, R.N. Sahoo.2014) has assessed SWAP model (Soil Water Atmosphere Plant) to its capability to simulate the salt dynamics and yield of three salt tolerant and one salt non-tolerant wheat varieties under different water irrigation regimes. The experiments were conducted at the research farm of Water Technology Centre, Indian Agricultural Research Institute, New Delhi, In dislocated in a semiarid monsoon climatic region. Four irrigation treatments viz. ground water (S1) salinity varying from 1.45 to 1.7 dS m−1, and saline water levels of 4 dS m−1(S2), 8 dS m−1(S3), 12 dS m−1(S4) wereused for irrigating the crop. The model was calibrated and validated using the experiment generated data of rabi 2009–2010 and 2010–2011 cropping seasons, respectively. The model performance indicators i.e. model efficiency (ME) and degree of agreement (d) was 0.76 and 0.93 for root zone soil salinity and0.96 and 0.99 for relative wheat yield of calibrated model, respectively. Furthermore, root mean square error (RMSE) and mean absolute error (MAE) for prediction of relative yield during calibration was 4%and 3% and during validation was 9.6% and 8.3%, respectively. The validated model performed well for salt dynamics in root zone and relative yields that were corroborated by prediction error statistics R2of 0.96 and 0.95, ME of 0.95 and 0.75 besides degree of agreement (d) of 0.98 and 0.93, respectively. It was observed that the model performed better for prediction of relative yield of salt tolerant varieties as compared to the salt non-tolerant variety under different saline irrigation water regimes. Overall, the SWAP model could be used to simulate the salt dynamics in the crop root zone and yield of wheat with acceptable accuracy under irrigated saline environment.

2.2 Soil contamination characteristics

Contaminant transport in natural aquifers is a complex, multi-scale process that is frequently applied using numerical methods. Conservative solute transport is typically modeled using the advection–dispersion equation (ADE). Despite the large number of available numerical methods that have been developed to solve it, the accurate numerical solution of the ADE still presents formidable challenges. In particular, the numerical solutions of multidimensional advection-dominated transport in non-uniform velocity fields are affected by one or all of the following problems: numerical dispersion that introduces artificial mixing and dilution, grid orientation effects, and unphysical numerical oscillations. (Paulo A. Herrera , Marco Massab , Roger D. Beckie, 2009), derived a new numerical method based on smoothed particle hydrodynamics (SPH) for the simulation of conservative solute transport in heterogeneous porous media. Model has demonstrated that the new scheme is stable, accurate, and conserves global mass. The results of those benchmarks demonstrate that the proposed scheme has important merit over other standard methods because due to its ability to control numerical dispersion and other numerical artifacts. On the other hand, while the numerical dispersion affecting traditional numerical methods creates artificial mixing and dilution, the new scheme provides numerical solutions that are ‘‘physically correct”, greatly reducing these artifacts.

As mobility of solute through a porous medium is concern, A number of publications have demonstrated that the size distribution of nano-particle suspensions can change during transport (Solovitch et al., 2010; Chen et al., 2011; Jiang et al.2012) Accurately predicting the fate and transport of graphene oxide (GO) in porous media is critical to assess its environmental impact. (Yuanyuan Sun, Bin Gao

,Scott A. Bradford, 2015) conducted sand column experiments to determine the effect of input concentration and grain size on transport, retention, and size perturbation of GO in saturated porous media. The mobility of GO in the sand columns reduced with decreasing grain size and almost all GO were retained in fines and columns for all of the tested conditions. This result can be explained with colloid filtration. Input concentration also influenced the retention and transport of GO in the sand columns because of the ‘blocking’ mechanism that limits the particle retention rate. In addition, the sizes of GO retained in the sand also increased with travel distance. These results suggested that transport through the porous media induced GO aggregation. A mathematical model based on the advection dispersion equation coupled with the second-order kinetics to reflect the blocking effect simulated the experimental data well.

An accurate porosity and permeability evaluation of rock formations is critical to estimate the quality and resource potential of a reservoir. In addition to directly measure the porosity and pore size distribution, low field Nuclear Magnetic Resonance (NMR) is able to measure the effective porosity and estimate the real formation permeability, though its robustness is arguable and requires calibrations on cores. (Antoine Dillinger, Lionel Esteban, 2014), have studied the consistency of the Nuclear Magnetic Resonance approach when compared to conventional helium injection method. A collection of cores was retrieved from three wells intersecting these units. The characterization of their flow properties complements the current evaluation of the Perth Basin by adding new data on effective porosity, pore size distribution, pore geometry and calibration of predictive models for the permeability according to a comprehensive faces classification scheme.

Infiltration of water in dry porous media is subject to a powerful gravity-driven instability. Although the instability of infiltration phenomenon is well known, its description using continuum mathematical models has posed a significant challenge for many researchers. (Hector Gomez , Luis Cueto-Felgueroso , Ruben Juanes, 2013) has present a computational study of a model of unsaturated flow in porous media that extends the Richards equation and is capable of predicting the instability and captures the key features of gravity fingering quantitatively. The outcome of that study has been illustrated the accuracy, efficiency and robustness of the method with several examples in two and three dimensions in both homogeneous and strongly heterogeneous media. In which it was shown its consistency with classical experimental observations that demonstrate a transition from stable to unstable fronts depending on the infiltration flux. The dynamics of water in the unsaturated zone is therefore a key to understand the underground flow regime characteristics.

Another feature of soil recharge is the normal irrigation process which may considered as very attractive subject for study and search in the recent years.(Usman Khalid Awan , Ali Ismaeel, 2014.) selected the Lower Chenab canal irrigation scheme, the largest irrigation scheme of the Indus Basin irrigation system as a model to estimate of groundwater recharge using the soil and water assessment tool. Simulation was done using the SWAT model for representative concentration pathways climate change scenarios for the period 2012–2020. In addition, actual evapotranspiration (ETa) was estimated using the SWAT model for the period 2010–2011. The results showed that groundwater recharge would increase by 40%, as compared to the reference period, by the end of 2020 even with climate change

Majority of environmental concerns over the past decades have made the need for computer models that demonstrate dispersion of pollutants / agents in global water systems an absolute necessity. In contrast to conventional models, computer models are primarily important because of its lower cost and their applicability to various situations. Thus, the popularity of mathematical modelling methods for hydrodynamics and pollutant migration in underground water justifies any trial to establish new models based on novel and more realistic approaches.

Seepage into soils is an important study in all petroleum engineering and environmental concerns. Two major domains are involved in underground media and the interfaces between free and porous flow regimes in the ground formation. Understanding these interactive phenomena and the way where these regions behave in combination represents a key element for the management of groundwater quality and control. Free and porous water flow in lands often occurs during the combination of different physical properties. To model such problem, open and porous flow regions need to be studied as a standalone and integrated through well-posed mathematical formulations. This study would require an investigation of the flow of water and the movement of contaminants in soil.

Determining factors for the mobility of contaminants, flows at subsurface domains have been studied in many occasions using seepage flow models (e.g., see Cedergren 1989; Das et al. 2002; Reddi 2003). These investigations concluded that flow regimes often have unstable characteristics, due to the heterogeneity of soils in which water flow is exist.

In contrast, underground reservoirs (water / oil) also involve coupled free and porous flow regions. However, the associated fluid transport phenomena are due to natural hydro-environmental conditions in the majority of these cases, such as seepage through preferential flow domains, the rise and fall of groundwater, and flow circulation. In general, form of the problem, the sub-domains in combined flow systems are distinguished by interface surface, which represents an essential transition zone for fluid movement. Furthermore, a combined transport process may include the movement of chemicals in a conjugate domain of a pipe and the surrounding soil (porous medium). At the macro-scale, the most notable cases include the transport of groundwater and solute from/to large cracks or cavities in lands to/from adjacent soil domains and the movement of contaminated water from a water table to nearby permeable soil beds (aquifer system). Although free and porous flow models are found in many other engineering applications (e.g., Salinger *et al.*, 1993, 1994; Nassehi and Petera, 1994; Gartling *et al.*, 1996; Nassehi, 1998), models of fluid transport underground have traditionally ignored the possibility of associated free and porous fluid currents in neighbouring sections. These fluid transfer models have described the entire physical zone as a single porous field (Darcian, etc.). Because the need for more realistic transport models of contaminants has increased, it has become necessary to identify the fluid dynamic characteristics of water in the differently behaving domains and link these areas through well-posed mathematical models. However, the realistic modelling of underground flow processes requires three-dimensional computations, which can be successfully performed if finite element methods are used. Other numerical techniques that can resolve such difficulties due to their mathematical strength include the finite volume (Patankar, 1980; Versteeg and Malalasekera, 1995) and spectral (Canuto *et al.*, 1988; Guo, 1998) methods. These methods should, therefore, be adopted to represent the underground fluid heterogeneity of the soil that arises for many reasons, such as the formation of staggered layers of soil with different porosities, as is the case for Kuwait aquifers. Therefore, realistic mathematical descriptions and models of water flow require that the projection of the problem and subjected boundary conditions that affect water flow are well formulated. The transport equations that describe the flow through porous media are dependent on the properties of the fluid and factors such as the permeability, porosity, and the geometry of the media.

This work aimed to demonstrate that there are a significant relation between the surface flow and underground conditions in unsaturated land. The simulation results obtained in this study can therefore be considered as a quantitative analysis of the link between these conditions. Rainwater flow over the top surface of unsaturated lands has the main influence on the interactions between the surface flow and underground porous regime. The main parameters that affect flow through soils are a hydraulic gradient (pressure differences) and the permeability of soil. The permeability is a function of the range of grain sizes and shapes, stratification, consolidation, and cementation of the material. The hydrodynamic conditions of the porous flow domain in the subsurface were analysed in the current work, with a focus on the fluid dynamic behaviour of the domains for different aspect ratios.

The flow models of these areas require descriptions of not only the fluid dynamic characteristics in the individual domains but also the mass and momentum transfer behaviour across the domain. The impact of the combined (water / agent) flow on the overall transport behaviour depends on many distinguishing features, such as the dimensions of the pathways, their behaviour in combination with the surroundings, and the characteristics of the porous material, e.g., the porosity with corresponding permeability. The number of permeable interfaces between the free and porous flow regimes and the aspect ratios of the sub-domains also influence the fluid dynamics. To model fluid flow in these domains, two approaches have to be considered for the modelling requirements: the formulations based on the assumption of continuum domains based on discrete pathways. In the former case, the porous section is treated as a pseudo-fluid layer, and the whole domain is considered to be a single domain. As such, one suitably formulated equation of motion is solved in conjunction with other equations for the continuity of mass and the pollutant species balance.

Mathematical models based on the multi-domain approach for most combined flows are well established for artificial flow systems (Nassehi and Petera, 1994; Gartling *et al*., 1996; Gobin *et al*., 1998; Nassehi, 1998; Chen *et al*., 1999). However, extension of these formulations to composite underground flow has been difficult. The main difficulty with this task is the realistic representation of flow behaviour at the interfacial surface, which stems from two main sources. The first is the inherent irregularity in the sizes and shapes of the domains. Second, the randomness can be related to the processes involved and the impossibility of an exhaustive analytical description. The model also necessitates the imposition of matching interfacial conditions to describe the flow behaviour of water through the porous media. Furthermore, the data must be visualised by graphical means not only to interpret the calculated results but also to determine the applicability and accuracy of the adopted technique. The shape and size of the interface for combined and free porous flow in the subsurface is expected to be random and lacks physical evidence for the mass and momentum transport behaviour across the interface. Therefore, to preserve the compatibility of the underground fluid dynamic characteristics at the interfaces, numerical schemes are usually used because they can address such problems. Finite element schemes are well known to readily cope with curved and complex problem domains.

2.3 Contaminant Transport and Remediation Processes

An accurate description of the flow of multiple fluid phases through a material which consists of a solid and interconnected pore space is highly relevant in several fields of application. This includes environmental and geological applications such as groundwater protection and remediation, oil recovery, nuclear waste disposal, carbon dioxide storage, dry-out and evaporation processes etc., but also technical systems such as the flow of water and gas in fuel cells or filters. In all of these cases, a quantitative prediction of flow and transport on strongly varying spatial and temporal scales is required and typically achieved with mathematical and numerical models. Numerical models for flow and transport in porous media are valid for a particular set of processes, scales, levels of simplification and abstraction, grids etc. The coupling of two or more specialized models is a method of increasing the overall range of validity while keeping the computational costs relatively low. Examples of applications for which these concepts can be relevant include groundwater protection and remediation, carbon dioxide storage, nuclear-waste disposal, soil dry-out and evaporation processes as well as fuel cells and technical filters. (Rainer Helmig , Bernd Flemisch , Markus Wolff , Anozie Ebigbo , Holger Class,2013).

Fluid flow modeling in porous media has many applications in waste treatment and management. In any geological model, flow behavior is controlled by multiple properties. These properties must be known in advance of common flow simulations. While facing uncertainties problem, conventional type of modeling often produces poor results. Percolation and Random Walk (RW) methods have recently been used in flow modeling. Their basis is useful in dealing with uncertainty problems. They are also useful in finding the linkage between porous media descriptions and flow properties. Simulation of multi-phase flow in porous media is a great subject in many disciplines, including contaminant hydrology and petroleum engineering. Modeling of multi-phase flow is difficult since the parameters involved (e.g., viscous, capillary, gravity and diffusion) may act at different scale level. The complexity of porous media also makes things more challenging. In enhanced oil recovery (EOR) processes, flow simulation requires numerically solving the governing partial differential equations (PDEs). (Mostafa Ganjeh-Ghazvini ,Mohsen Masihi ,Mojtaba Ghaedi, 2014.) Has employed a simple methodology based on random walk and percolation techniques. The method is applied to a well-defined model reservoir in which the breakthrough time distributions are estimated. The results of the applied method and the conventional simulation are then compared for the aim of validation.

Thermal remediation is a common technology used in the groundwater sector to deal with organic pollutants such as dense non-aqueous phase liquids (DNAPLs) (Buettner and Daily, 1995; Sleep and Ma, 1997; Sleep, 1999; Sleep and McClure, 2001a; Heron et al., 2013). Thermal technologies include steam or hot water injection, thermal conduction heating, radio frequency heating (RFH), and electrical resistance heating (ERH). All these technologies increase the subsurface temperature, resulting in an increase in contaminant volatility. The existence of subsurface buoyant flow during thermal remediation was investigated (Magdalena M. Krol , Richard L. Johnson , Brent E. Sleep, 2014) using a two dimensional electro-thermal model (ETM).The model has been used to study the effects of heating on sixteen subsurface scenarios with different groundwater fluxes and pore permeability .It was noticed that when the buoyancy number was greater than unity and the soil permeability greater than 10−12 m2, buoyant flow and contaminant transport were significantly high. Another aspect of that study was the effects of low permeability layers and electrode placement on heat and mass transport .Where, it was concluded that heating under a clay layer would lead to flow stagnation zones resulting in the accumulation of contaminant mass and transport into the low permeability layer. The outcomes of this study can be used to develop dimensionless number-based guidelines for site management during subsurface thermal remediation process.

Groundwater is a fragile resource; once contaminated, it is difficult to remediate (Davis et al., 1999). During the past years, many studies have been conducted to physically simulate the transport with remediation process of petroleum hydrocarbons in subsurface systems (Lakhwala et al., 1998; Shook et al., 1998; Annable et al., 1999). Reviews of previous physical modelling studies have been published by Sabatani et al. (1995, 1999) and Nataatmadja (1996).

Most of the physical modelling studies were focused on laboratory- and field-scale experiments (Pinto et al., 1997; Walker et al., 1998; Zhu and Sykes, 2000b). Gonen and Gvirtzman (1997) studied laboratory-scale aquifer remediation using recirculation airlift pumping. The authors indicated that the removal of volatile organic compounds depended on their ability to volatilise inside the well into the air bubbles and its ability to desorbs from the aquifer formation into groundwater. However, at field-scale conditions, in which sorption and desorption played a significant role; the efficiency of the mechanism could be effectively reduced. In a column experiment study conducted by Fortin et al. (1997), the effectiveness of the surfactant solution at removing the light non-aqueous phase liquid (LNAPL) and dense non-aqueous phase liquid (DNAPL) was evaluated. The study showed the negligible sorption of surfactants on the aquifer material. The authors concluded that the solubilisation and emulsification of NAPLs by the surfactant solution were rate-limited.

Bettahar and Razakarosoa (1998) conducted laboratory experiments to study the surfactant flow behaviours and effects of co-solvents on the remediation of diesel oil in a contaminated aquifer. Study showed that the reduction of permeability, which causes the plugging of porous media during surfactant remediation, was due neither to the precipitation of the anionic surfactants in the presence of calcium ions nor to the clay mineral present in small proportions in the porous medium. Rather, the reduction of hydraulic conductivity was due to the instability of the surfactant solution. The addition of a co-solvent facilitated the dispersion of the aggregates of mixed surfactants, and it significantly increased the recovery of oil trapped at residual saturation in the soil. This method presented a means of predicting and manipulating the vertical migration of a micro-emulsion containing solubilised trichloroethylene (TCE) to minimise buoyancy-driven flow. The contamination of soils and groundwater resources is of growing environmental concern. C. T. Simmons (2001) investigated a sand-filled glass flow container under saturated and variably saturated conditions and focused on the effect of the migration of dense contaminant plumes through the unsaturated zone on the capillary fringe and area below the water table. In addition to the fluid density gradients and permeability of the porous medium, which determine the onset conditions for instabilities in fully saturated experiments, the volumetric water content appears to be critical to the variably saturated laboratory runs. The plume behaviour at the water table appears to depend on the density of the fluid that accumulates there. For neutral- and low-density fluids, plumes accumulate at the water table and then spread laterally above it, and the water table forms a barrier to further vertical flow as pore water velocities decrease with increasing water content. For medium- and high-density fluids, the vertical movement continues as instabilities form at the capillary fringe and fingers begin to grow at the water table boundary and move downwards into the saturated zone. In these cases, the lateral spreading of the plume is small. Despite these more qualitative observations, the exact nature of the relevant stability criteria for the onset and growth of instabilities in variably saturated porous media presently remains unclear. The unsaturated zone and position of the water table must be considered in contaminant studies to predict the migration pathways, rates, and ultimate fate of dense contaminant plumes. They also provide a strong basis for the development of more rigorous mathematical formulations that are likely to be either developed or tested using numerical flow and solute transport simulators.

Walker et al. (1998) investigated the treatment of perchloroethylene (PCE) through two-dimensional saturated porous media consisting of a low-permeability sand layer situated in high-permeability soil. The porous zone flushed with different surfactants and co-solvent formulations injected at the PCE source location and extracted below of the porous medium. The clean-up of PCE in most of the high-permeability sand was considered to be significant. PCE accumulated on the top of the fine layer, but posed a significant challenge for remediation process and requires several pumping configurations.

.Dwarakanath et al. (1999) demonstrated a variety of column experiments for the selection and evaluation of suitable surfactants to remediate DNAPLs. The study reported that up to 99.9% of DNAPL is the recovery from a soil column in 1 to 2 pore volumes of surfactant flooding.

Oostrom et al. (1999) and Walker et al. (1998) conducted a similar experimental study using pump-and-treat and surfactant-flushing (SF) techniques to remove a TCE spill from a saturated porous medium. Based on the extraction rates and measured TCE concentrations, the result showed that only approximately 60% of TCE was removed after remediation, 40% was moved downwards into the fine sand as a result of the mobilisation of the pure phase.

Cromwell and Albertz (1994) remediated soil and groundwater using a variety of techniques. Due to equipment costs, the removal efficiency, and the method of discharge, groundwater collection and treatment with activated carbon and soil vapour extraction were selected as preferred methods. Following 18 months of operation, the groundwater remediation system reduced the benzene concentration in groundwater by 99.7%.

Falta et al. (1999) have studied the design and relevant performance of a co-solvent test to mobilise NAPL. The results of soil coring indicated 90% removal of more soluble contaminants and 70 to 80% removal of less soluble compounds. Brusseau et al. (1999) and McCary et al. (1999) investigated a remediation technique termed complexing sugar flushing used cyclodextrin, a sugar (glucose)-based molecule, to enhance the aqueous solubility of organic contaminants. The studies indicated that this molecule might be useful when the dissolution of NAPL into a flushing solution is significantly inhibited due to mass transfer rate limitations.

Gierke et al. (1999) conducted a controlled field study to assess their sparging performance to remediate petroleum contaminants in a shallow groundwater aquifer at Hill Air Force Base, Utah. It was noticed that rate of contaminant removal by volatilisation due to air sparging was higher than that of the conventional pump-and-treat system.

A similar study was conducted by Blandford et al. (1999) to evaluate the performance of a vertical recirculation well equipped with an in-well air stripper at the same site in Utah. The air stripping system could remove 26% high dense of ten representative contaminants from water passing through the well. The net magnitude of remediation was below (< 1%). Garcia et al. (2000) has performed a bench-scale and tank-scale systems to determine the transport parameters in heterogeneous aquifers. Similarly, Iangasekare et al. (2000) demonstrated a pilot-scale laboratory evaluation of subsurface restoration technologies for a diesel- contaminated site at different water flow rates.

Additional related research can be found in papers by Francois et al. (1996), Davis et al. (1999), and Bedient et al. (1999). The earliest work on the multiphase flow modelling of petroleum hydrocarbons appeared in the European literature. van Dam (1967) was the first to model an oil spill scenario as a two-phase flow system. The author analysed the infiltration of oil through the porous zone and its migration along the water table surface using the conceptual laws governing multiphase flow. Although he discussed the importance of capillarity in multiphase flow analysis, the author assumed that capillary effects were negligible.

Many other studies have also neglected capillary effects (Hochmuth and Sunada, 1985; Corapcioglu and Hossain, 1986). This assumption treats the flow of oil contaminants in groundwater as a sharp interface problem, which inherently sets the saturation of the existing phases to a constant value. In other words, the two phases cannot coexist in a pore space, i.e., the pore space can only be occupied by either oil or water. Thus, the applicability of these models was limited to a very narrow class of realistic problems.

Abriola and Pinder (1985a, b) considered the partitioning of the organic components into gas and water phases, the compressibility of fluid and medium, and the influence of the organic phase densities and viscosities on the composition. They employed the implicit finite difference scheme to discretise the governing equations and solved the resulting equations using the Newton-Raphson techniques. They then applied the model to two- and three-phase flow scenarios in saturated and unsaturated zones.

Kuppasamy et al. (1987) has introduced simplified three-phase flow model, by maintaining a constant gas-phase pressure and neglecting porous matrix and fluid compressibility. They expressed the governing equations as primary variables in terms of the phase pressures. They replaced the time derivatives with a variable-weighted finite difference representation and solved the nonlinear algebraic discretised equations via a relaxed Picard iterative scheme. The authors then validated their model against the experimental results from one-dimensional experimental settings. Organic contaminants are considered as the most common health-threatening chemicals analysed in groundwater. Majorities of these contaminants have shown in very low solubility and are generally immiscible in water. Therefore, these compounds migrate through the subsurface as non-aqueous phase liquids (NAPLs) and can be categorized as either lighter than water (LNAPLs) or denser than water (DNAPLs). DNAPLs, such as chlorinated solvents, creosote, and PCB-rich oils, pose a particular problem in the subsurface environment because they have the potential to migrate to reach a high depths below the water table.

Annar Mason (1996) presented a one-dimensional numerical model that shows surfactant-enhanced solubility of pooled DNAPL in which two non- equilibrium expressions involving mass transfer are examined. The mass transfer coefficient was dependant on wetting phase Darcy flux, with the mass transfer rate coefficient accounting for the variance of interfacial area available for mass transfer between the DNAPL and the surfactant solution through the pool and over time. The model has been tested using experimental data from laboratory column, in which pooled tetra-chloroethylene was solubilised under upward gradient conditions. Effluent from the system were successfully predicted by the developed model, although simulated effluent curves exhibited more tailing than the experimental data.

The massive release of domestic and industrial effluents has become a primary cause of environmental contamination, including groundwater resources, all over the world. Several resources and aquifers have affected, contaminated by highly toxic and mobile hexavalent chromium. Jeyasingh (2011) conducted pilot-scale studies to assess the suitability of the bioremediation of Cr (VI)-contaminated aquifers using bio-barrier and reactive zone technologies that use chromium bacteria. The experimental results observed that a 10 cm thick bio-barrier with an initial biomass concentration of 0.44 mg/g of soil was able to recover a 50 mg/L Cr (VI) plume when the Darcy velocity was 0.0196 cm/h. In the case of reactive zone technology, a system with four injection wells was effective even when the Cr (VI) concentration in the plume was as high as 250 mg/L if 150 g (wet weight) of bacteria were injected into each injection well.

2.4 Numerical Simulation of Contaminant Transport

Multi-modeling problems have received a wide publicity over the past years due to their applications. Mainly in the mixed Stokes–Darcy model (Liyun Zuo, Yanren Hou, 2014), which describes the coupling of the fluid flow (governed by the Stokes equations) with the porous media flow (governed by the Darcy equations) through certain interface and boundary conditions. It was appeared that solving this coupled model usually results in difficulties, especially in the numerical problems. The interest in the decoupling process, in which the coupled approach can be separated into two single flow problems. This allows using appropriate methods for solving each problem independently, and numerical implementation is remarkably efficient. In this context, consider the mixed Stokes–Darcy problem, which describes a fluid flow coupled with a porous media. The presented modified two-grid method for decoupling where Stability is proved and optimal error estimates are derived.

There is a clear need for test cases against which results from porous media flow and transport codes can be compared. This is especially true for more demanding problems such as density-dependent flow. Flow and transport in saturated porous media may be influenced, or even dominated, by phenomena of variable-density flow, if solute concentration gradients are high. The numerical codes used for simulation of these situations have to be tested in order to ensure their reliability (S.E. Oswald, W. Kinzelbach. 2003) has performed a series of laboratory experiments with well-defined experimental parameters for a typical variable density problem to provide data for such a test. A Nuclear Magnetic Resonance Imaging technique was used, which was powerful for determining three-dimensional salt concentration profile in a porous medium with respect to time. Two experiments were conducted with 1 and 10% salt mass fraction as initial salt concentration calculation. These experiments were done twice to determine experimental parameters and to check the behavior for intermediate salt concentrations. The set-up comprised of a stable layering of the saltwater below freshwater, affected by recharge and discharge of water at the surface. The condition is comparable to the upward saltwater–freshwater interface due to pumping. Numerical simulations were constructed with a variable-density flow code and the results compared with results from the laboratory experiments. It is shown how these experimental data can be utilized as a benchmark test for variable-density flow models.

Efficient and accurate evaluation of the flow velocity is a prerequisite for constructing any numerical model of contaminant transport through porous media. The requirement of efficiency becomes more essential for simulations of heterogeneous medium, as typically hundreds of realization is required to obtain a realistic description of the transport process. An accurate representation of the velocity field is especially critical to the performance of numerical models based on the particle tracking technique. With realizing of the complexity of transport and in the absence of usable analytical expressions, numerical modeling has become the method of choice for field scale transport simulation. The Finite Difference Method and the Finite Element Method are the two most commonly used numerical techniques for groundwater flow and transport. Obviously, the numerical methods first solve for the hydraulic head (potential) at the grid points and then obtain the velocity by numerical differentiation. This results in a loss of one order of accuracy in the velocity computations and gives rise to discontinuities in velocity components at the element boundaries. For numerical modeling of transport of contaminants through porous media, an accurate determination of the velocity field is a prerequisite. Some previous schemes of obtaining the Darcian velocity field through numerical solution of the flow equation result in a physically inconsistent velocity distribution in a heterogeneous medium. A scheme that is consistent with the physics of velocity variation near material interfaces is examined and compared with previous schemes. Numerical simulations are used (Rajesh Srivastava & Mark L. Brusseau, 1995), to demonstrate the capability and accuracy of the proposed scheme for randomly heterogeneous porous media.

The applicability of Darcy law in fluid flow and heat transfer through porous medium have been considered as a point of interest in the past decade in many publications by searchers. This is primarily because of highly number of applications of flow through porous media, such as storage of radioactive nuclear waste materials transfer, separation processes in chemical industries, filtration, transpiration cooling, transport processes in aquifers, ground water pollution etc. (Cheng and Minkowycz, 1977; Kumari et al., 1985; Plumb and Huenefeld, 1981). Mixed convection flow along vertical surfaces in a porous medium has been studied by several investigators. (S. Jayanthi, M. Kumari, 2006), analyzed the variable viscosity effects on non-Darcy free or mixed convection flow on a vertical surface in a fluid saturated porous medium. The viscosity of the fluid is assumed a linear function of temperature. Velocity and heat transfer are found to be significantly affected by the variable viscosity parameter, Ergun number, Peclet number or Rayleigh number. Forced convection heat and mass transfer from a porous and nonporous sphere to a non-porous/porous surrounding medium was studied in many problems. (Gheorghe Juncu, 2014) investigated numerically the steady conjugate heat transfer from a composite sphere to a surrounding fluid flow for low Reynolds numbers values. The composite sphere has a solid, impermeable, isothermal core surrounded by a shell of homogeneous and isotropic porous medium. The flow in the porous shell is described by the Brinkman’s equation. The effects of the porous shell thickness, permeability, and thermal conductivity on the heat transfer rate were studied. The momentum, heat and mass transfer between a sphere and a surrounding medium is one of the classical benchmark problems for the analysis of transfer phenomena with broad applications in many environmental, industrial and life-science processes.

Both porous media are fluid saturated. Local thermal equilibrium between the two phases is assumed. The fluid flow inside and outside the sphere was considered axisymmetric, steady and incompressible (Darcy and Brinkman flows). The heat balance equations were solved numerically in spherical coordinates system by an implicit alternating direction finite difference method. The influence of the porous media permeability and sphere Peclet numbers on the heat transfer mechanism and rate was analyzed for different values of the physical properties ratios.

Multi-phase flow has been presented (Eduardo Abreu, 2013), a new numerical formulation for the simulation of immiscible and incompressible three-phase water–gas–oil flows in heterogeneous porous media .The method is used to investigate the question of existence, and structurally stable, of three-phase flow solutions for immiscible displacements in heterogeneous porous media with gravitational effects. The new formulation is a sequential time marching fractional-step procedure based in a splitting technique to decouple the equations with mixed discretization techniques for each of the sub-problems: convection, diffusion, and pressure–velocity. In this field of study, concerned in dynamic fluid flow processes in heterogeneous reservoirs where both the convective flux and diffusion functions have a spatial discontinuity

Kaluarachchi and Parker (1989, 1990) developed a two-dimensional finite element model to predict coupled transient flow and multi component transport of organic chemicals, which can be segregated into oil, water, gas, and solid phases in porous media under certain thermodynamic condition. The gas-phase pressure gradients were assumed negligible, and the liquid flow equations were solved simultaneously using an upstream weighted solution method with time-lagged inter-phase mass-transfer terms and phase densities. The phase-summed component transport equations were also serially solved using an upstream finite-element method after computing the velocity field. The authors examined the numerical performance of an upstream-weighted Picard procedure for handling the nonlinearity of the flow equations compared with the Newton-Raphson method. According to the results of this study, the Picard method without upstream weighting caused instabilities that inhibit convergence. Additionally, the upstream weighted Picard technique provided satisfactory results and required less computational effort than the Newton-Raphson method. In addition, the authors investigated the conservation of mass balance. The accuracy of the mass balance depended on the formulation used for the saturation-pressure derivative terms and the scaling parameters of the constitutive relationships.

Sleep and Sykes (1993a, b) has produce a well performed a three-dimensional, three-phase finite difference multi-component simulator that analyses the contamination and remediation process involving groundwater systems. The simultaneous phase flow (water, gas, and organic) and the inter-phase partitioning and transport of an arbitrary number of organic and inorganic components were modelled. The phase densities were functions of pressure and phase composition, and the viscosities were assumed functions of phase composition. The authors used a block-centred finite difference scheme to discretise the flow and transport equations and explored different numerical methods to maximise the computational efficiency. The model consists of several numerical techniques, ranging from fully implicit with first-upstream weighting to implicit in pressure and explicit in saturations and concentrations with third-order upstream weighting. The model was validated against available analytical solutions of three-phase flow and single-phase solute transport.

Prommer et al. (2000) modelled groundwater contamination by BTEX (benzene, toluene, ethylbenzene, and xylene) using a 2-D PHTRAN model based on a split-operator approach. The authors briefly discussed the capabilities and limitations of various models used previously to describe the behaviour of solute transport in aquifers. They indicated that an interdisciplinary approach was required to tackle environmental problems involving scientific underpinning in the areas of geochemical reaction processes, groundwater hydrology, and soil microbiology.

Clement et al. (2000) developed a multi-component biodegradation reaction model to validate the natural attenuation processes generating at a chlorinated solvent release site. Paula predicted contaminant transport through soil site. The model was employed to certain case study consisting of permeable soil with an initial concentration in the thin surface of an unconfined aquifer. The site characteristics werefound to most significantly affect the predicted soil-water volumetric flux rate in the unsaturated zone and the Darcy velocity in the saturated zone. This input parameter yielded a cumulative distribution function for the total risk estimate. Gallo and Manzini (2001) developed a numerical model that coupled the phase pressure and saturations in two-phase flow, NAPL concentration transport, and biodegradation kinetics. A mixed-hybrid finite element model incorporated the non-linear saturation dependence in Brooks-Corey relative permeability and capillary pressure effects. A finite volume method considered the contaminant transport, which also incorporated the non-linear degradation kinetics as a suitable source term.

Sun et al. (2002) developed a mathematical model to describe the transport of multiple volatile contaminants in the unsaturated zone with the phase partitioning of sequentially reactive species under constant flow velocity conditions. Linear reaction kinetics and linear equilibrium partitioning between the vapour, liquid, and solid phases were assumed in this model. The disposal of wastes and contaminated water in landfills is a common problem in industrial countries, which frequently resulted in environmental pollution (Ball et al., 1995). In the oil-rich, affluent, and rapidly developing nations of the Arabian Gulf region, growth in population and advancing urbanisation, combined with rising personal income, will defiantly resulting in a significant increase in the amount of solid waste generated in the cities of the region. Municipal solid waste (MSW) landfills are associated with the generation of highly polluted leachate. Contaminant migration from disposal sites to groundwater poses a threat to the environment and natural water resources in the country. Anwar Al-Yaqout (2004) has studied the contaminant fate at a landfill area in Kuwait. The transport characteristics of contaminants were analysed using advanced computing systems to predict the long-term plume concentration in underlying soils formation and aquifers below the disposal area. Mathematical models of contaminant migration were applied to existing disposal sites using the MIGRATEv9 computer program to demonstrate the scope and extent of soil and water contamination.

Two main cases were modelled as follows:

- The water table below the landfill area.
- The water table, which is rising at the subsurface area.

The models included devective dispersion and buried landfill systems. A comparison between the model results shows that the vertical Darcy velocity significantly affected the migration behaviour of contaminants. The concentration increased by 24.5% when the Darcy velocity was increased from 0.005 to 0.009 m/year. Advection–dispersion models and water rising models with a fixed top boundary and aquifer bottom boundary at 2 and 3.5 m showed almost the same migration behaviour.

Serge Bruyere (2007) proposed a new tracking technology, which is circulated dilution method from one point also to the limited volumes of fluids and trace the flow of water, known as the limited size of point dilution method (FVPDM). It is based on the analytical solution derived from a mathematical model to model accurately trace injection wells. Using non-dimensional formulation of the analytical solution, a sensitivity analysis was performed on the focus changes in the injection well and according to the circumstances of tracer injection well and interactions aquifer. The new tracking technology is easier to implement in the field of dilution method classical point of view, and allows monitoring of temporal changes to the size of the estimated Darcy flows. This technique has been applied to two pilot sites with different geological and hydrogeological conditions, facilities and equipment in the field. The results were very satisfactory modeling indicated that effective and accurate methodology, and contains a wide range of potential applications in different environments and experimental conditions, including the monitoring of temporal changes in Darcian flow.

The simulations of groundwater pollutant fate and transport and treatment topics vary as seen from intensive research in recent years. Helen and Yang (2012) used a simulation package, PREMChlor, to simulate the effect of the source of pollutants and processed column at the site contaminated with trichloroethylene

(TCE), been calibrated model PREMChlor to a column using a policy imperative to represent the conditions of the site before reclamation activities, which took place in 1999. Then calibrated model was used in the development of probabilistic source to simulate the effects of field and feather reform activities.This simulation considered uncertainties in seven key parameters: the initial source mass and concentration, the relationship between source mass removal and source concentration, the effectiveness of the source remediation, the groundwater velocity, the background plume degradation rate, and the plume treatment effectiveness.

The mathematical modeling of incompressible stokes flow and low permeable Darcian flow has been introduced by Nassehi(2004) . In this regard, they represent a model of a limited quantitative prediction and analysis of hydrodynamic behavior of deadened pleated cartridge filters. The researchers showed that the developed simulation model could be expected to yield accurate realistic and industrially relevant problems. Model has been tested for shear thickening non-Newtonian fluid, which represents the fluids used in aviation applications and some process industries. Developer model has been demonstrated to support economic evaluationsPredicting the concentration profiles of solids being carried by the fluid stream in these types of low domains is a necessary factor in the design used in such operations. The above study provided a very convenient technique to simulate the concentration profiles of these types of domains. This approach primarily consisted of a very simple technique to handle concentration boundary conditions along the porous domains. The model could take process-dependent changes of physical parameters into account, which inevitably occur as a portion of the fluid seeps through the porous wall in these domains.

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Hussein and Hoteit (2007) also numerically modelled two-phase flow in heterogeneous permeable porous medium. Variationin the capillary pressure of heterogeneous permeable media can significantly affect the flow path direction in two-phase immiscible flow. Capillary continuity and in some cases capillary discontinuity may cause a discontinuity in saturation, which arises from a contrast in capillary pressure functions in heterogeneous permeable media, causing complication in numerical modelling. On the other hand, unstructured grids present another challenge to predict an accurate numerical modelling because of the grid orientation and numerical dispersion effects. The basic mixed finite element (MFE) framework is a more advanced method to get an accurate calculation of flux in heterogeneous media compared with the conventional finite difference and finite volume approaches.

Epshtevn et al. (Epshteyn, B. Riviere 2006) presented two schemes adopting discontinuous Galerikin methods to model perfect formulations of two-phase flow problems compromising of porous media. The model takes into account the convergence with according to uniform network refinement or an increase in the polynomial degree. Comparing with different discontinuous schemes, numerical examples of homogeneous and heterogeneous media on unstructured meshes determine the robustness of the method. Understanding the multiphase flow characteristics is crucially important to agencies concerned with energy, especially in oil industry. This study addresses modelling of two-phase flow, i.e., the flow of a wetting phase (aqueous liquids) and a non-wetting phase (non-aqueous liquids), in a porous medium with heterogeneous properties. This type of flow is mathematically simulated using partial differential equations (PDEs) that describe mass and momentum conservation laws, which is solved by using numerical methods.

Another type of two-phase flow simulation of porous media has been presented by Stevensona and Ferera (2006) to study the effects of heterogeneity and viscosity. The extent of porous medium heterogeneities versus the fluid properties in determining the effectivenessof various strategies for fluid injection into porous media has long been uncertain. In such study, both were shown to be considerable in determining the flow features. They also found that the coefficient of variation is a reliable predictor of the injected fluid saturation and the width of the interfacial area for a variety of statistical distributions of pore-throat radii. Moreover, they discovered that the viscosity ratio leads to a convergence from fractal viscous fingering to standard compact flow at a characteristic crossover time, which differs inversely with the viscosity ratio.

Barenblatt et al. (2007) have studied the non-equilibrium effects by introducing a pair of effective water and gas saturations, which are linked to the actual saturations by a local evolution equation, by proposing an extension to three-phase flow, i.e., non-equilibrium formalism, for two different porous media flow. Ruben and Juanes (2008) illustrated the non-equilibrium effects, which is leading to qualitative and quantitative differences in the solution of the three-phase flow equations.

Galusinski and Saad (2007) introduced a combined model of flow of two compressible and immiscible phases in a three-dimensional porous medium. The equations were derived from mass conservation of each phase. This model was illustrated into its generalized form with completely nonlinear terms. The primary assumption concerned is the dependence of densities on the global pressure, obtained weak solutions at different types of degeneracy of the capillary terms.

The water overflow of high temperature porous medium, in which two complicated flows was likely exist, has been investigated. A better understanding of the flow at the pore level noticed to be essential to justify and improve closure laws of macroscopic models. The features of two-phase flow in complex geometries can be predicted by using two approaches: experiments with high accuracy by collecting local measurements or direct numerical simulation (DNS) of the flows in small volumes. Within firm study, the second gradient theory, flow interface models can be derived for both single binary fluids. The latter model is often referred to as the Cahn–Hilliard model. The Cahn–Hilliard model is used to run two-phase immiscible flows in a representative geometry of a particle bed. The results were used to construct the configuration of the phases and possible flow regimes as a function of the saturation (Fichot and Meekunnasombat, 2007).

By considering mixture theory, Jian-Fei Lu and Andrzej Hanyga (2006) have produced a linear isothermal dynamic model for a saturated porous medium by two immiscible fluids. The volume fraction of each phase was limited by the saturation of the wetting phase and the permeability of the porous medium. The mass and momentum balance equations were calculated according to the generalised mixture theory. The isothermal constitutive relations for the stress and pore pressure were predicted from the entropy gradient of the porous medium. Three types of mechanisms were introduced in terms of the entropy inequality. The drag force model was introduced to account for the attenuation due to global fluid flow between the fluids and the solid skeleton, whereas the capillary pressure and the porosity relaxation mechanism were used to describe the relaxation process related to changes in the saturation and porosity. The capillary pressure relaxation mechanism is dependent on the interface between the two fluids, whereas the porosity relaxation mechanism is related to the local fluid flow within the porous medium.

Das and Nassehi (2001) applied a closed system analysis to a three-dimensional volume model. The model was applied to simulate groundwater hydrodynamics in domains representing combined free flow and porous sections, assuming that the free flow section is isotropic, the porous section is saturated, and the porosity of the anisotropic medium is constant.

In this paper, two types of simulations were applied:

- The Navier-Stokes equations were used to simulate the free flow regime.
- The porous flow was modelled by the Darcy equation.

Consequently, the two governing equations of motion were combined at the free porous flow interface. At the discharge from this interface, the “no boundary” condition was applied to avoid forcing any artificial condition on the flow system. This approach was recommended based on previously published works that support the reality of the simulation to describe this type of two-phase system. This work showed that the pressure is the driving force in porous media and that the pressure distribution among the domains may create an underground flow circulation inside the pores. This study also demonstrated that the direction of the porous flow might reverse at the interface over time.

Parvazinia and Nassehi (2005) applied Newtonian fluid flow to a case study of isothermal flow in a highly permeable porous medium between two parallel plates. They used Brinkman equation, which requires excessive mesh refinement to more stable and accurate results. A free method was used to derive suitable bubble functions for the implication of finite element discretisations. The results demonstrated that the Galerkin method could provide accurate and stable solutions for multi-scale problems. Parvazinia and Nassehi (2006) also modelled the or thermal flow of shear-thinning fluids in a porous medium between two impermeable parallel walls by using the Brinkman equation. Different Darcy parameters and power law indices were also studied. The Brinkman equation was solved by either by

- An analytical solution, based on a trial and error procedure.
- The finite element method, by limiting the range of the Darcy parameter and power law index.

The flow of shear-thinning fluids in a highly permeable porous media was studied by both analytical and finite element methods. The analytical solution was based on a trial and error procedure that was used for a wide range of Darcy parameters and power law indices. Although the finite element method generally fails to generate stable and correct results even with a high degree of mesh refinement, it can yield accurate results over a limited range of Darcy parameters and power law indices. Changes of fluid phase through the permeable porous media were studied, but the Darcy law would be useful in our plans to model the fluid flow in porous domains.

CHAPTER 3

FIELD STUDY ANALYSIS

3. Field Study Analysis

3.1 Groundwater pollution in the Ahmadi area

The groundwater pollution in the Ahmadi area is without parallel. Therefore, conventional methods of studying groundwater pollution by petroleum hydrocarbons cannot be used in this study. The significant reasons for this limitation are determined by the soil and contaminant characteristics.

The major differences between a conventional pollution problem and the present problem in the Ahmadi area are as follows:

- Size of the source of pollution: the ground surface contaminated is vast. Large amounts of hydrocarbons have accumulated over the Ahmadi area. Furthermore, unexpected leaks may occur due to pipeline rupture or poor maintenance. Land pollution of the size and magnitude experienced in the Ahmadi area is unprecedented.

- Nature of pollutants: the majority of land surface pollutants consist of the light components of petroleum hydrocarbons, such as petrol, diesel, and crude oil. The behaviour of the heavy component over the ground surface is poorly understood.

- Complex pathways: in conventional pollution, the path of movement of pollutants from the ground surface to the water table is well defined. In the present case, the unique geomorphologic conditions have resulted in complex pathways for the movements of pollutants.

- Weathering: the crude oil and hydrocarbon spread over the ground surface in the Ahmadi area is subject to severe weathering. This weathering results in the evaporation of light components, which changes the properties of the pollutants over time.

3.2 Surface pollutants

Vast areas of the ground surface have been polluted by crude oil or hydrocarbons leakage. Seven distinct sources of pollution can be identified in the Ahmadi area:

1. Crude oil that accumulated in oil lakes.
2. Hydrocarbons spilled from product storage tanks.
3. Seawater used to extinguish oil fires.
4. Subsurface leaking upstream or downstream of the pipe.
5. Large volumes of combustion products in the atmosphere.
6. Oil refinery wastewater.
7. API oil separator.

At the ground surface, the main sources of contamination are hydrocarbon spells, contaminated water from firefighting, and flue gas from the stacks (FCC stack) and flare system. Other forms of pollution originate from damaged storage tank leaks. The movement of oil contaminants through the unsaturated zones and aquifer units are largely controlled by geological, hydrological and groundwater flow conditions. A highly permeable zone would assist the rapid movement of contaminants.

Conversely, a highly dense zone will inhibit the movement of contaminants. As such, a better understanding of the mechanisms of local regional settings is essential.

3.3 Distribution of Pollutants

The distribution of pollutants at the ground surface changes over time because of the following factors:

1. Wind-blown sand, which shifts some of the products of combustion or leaks.
2. Run-off and infiltration of rainwater, which transports part of the pollutants.
3. Evaporation of accumulated oil in lakes or in the refinery water oil separator (called API separator).
4. Microbial degradation of oil.
5. Clean-up measures undertaken by the Kuwait Company.

Combustion products were almost non-existent at the ground surface, likely because of rainwater runoff and the shifting of combustion products to more central depression areas. In addition, wind-blow sand covered most of the soot material with sand of varying depths. The products of combustion transformed into hard, palletised soot in some areas, which can most likely be attributed to weathering. Many of the oil lakes were drained, and the oil was recovered. Some of the oil lakes were closed, and these became oil sludge and oil-polluted soil.

Moreover, the Kuwait Petroleum Company has constructed a new lake for the collection of oil from the surrounding oil lakes. This construction aimed to facilitate the easy recovery of oil, which would extend the surface and subsurface pollution areas to unpolluted lands in the form of oil sludge. This sludge consists of oil mixed with soil, soot, and soil with absorbed crude oil components.

3.4 Infiltration Rates

The infiltration of hydrocarbon into the subsurface regions is limited to a maximum depth of 3 m in the Ahmadi Area (KISR 2003). However, rainwater, which leaches the pollutants from oil-polluted soil, could rapidly infiltrate and reach the groundwater table within a very short time and contaminate the groundwater. The time taken for rainwater to move from the ground surface to the water table depends on the path taken by infiltrating rainwater.

The maximum rate at which water can move into the soil is called the infiltration capacity or potential rate (Bouwer, 1978). This is the rate that will occur when the supply of water at the surface is not limiting, as when the soil is covered by bonded rainfall, surface runoff, etc. All the rainwater will infiltrate if the rainfall intensity is less than the potential infiltration rate. If the rainfall intensity exceeds the potential infiltration rate, then the excess rainwater cannot move into the soil and will produce surface runoff. The potential infiltration is highest at the beginning of an infiltration event but decreases as infiltration continues and the wetted zone in the soil expands downward. The potential infiltration rate may eventually become constant.

The infiltration rate is one of the important parameters in the study of groundwater pollution within the Ahmadi region. The infiltration rate controls the movement of rainwater from the ground surface to the water table. Thus, we focused on the effects of the rainwater on the infiltration rate using FEMLAB model because the rainfall plays a key role in the pollution of groundwater.

3.5 Kuwait Rainfall Measurements

In Kuwait, rainfall mostly occurs during the winter in the form of showers and thunderstorms over a short period, with an average rate of approximately 120 mm/yr. Evaporation ranges from approximately 3.3 mm/d to 16 mm/d. The contaminants are transported from the ground surface to the groundwater by rainwater. Hence, rainfall plays a major role in the contamination of groundwater. The annual rainfall in Kuwait is approximately 110 mm. Table 3-1 shows the rainfall measurement over the past few years.

Table 3-1: the rainfall measurements in the Ahmadi Area

	Rainfall (mm)			
Month/Year	2005-2006	2006-2007	2007-2008	2008-2009
September	0	0.2	0.6	0.2
October	0.4	0	7.2	0.8
November	31.7	1.3	11.6	15.8
December	19.4	1	60.4	31.6
January	25.9	47.2	21.3	39.4
February	8.6	70.7	7.5	9.1
March	57.3	26.9	2.8	6.6
April	1.1	0.9	2.1	1.2
May	3.3	0	0.5	2.7
Total	147.7	148.2	114	108

3.6 Classification of groundwater pollutants

Petroleum hydrocarbons are a complex mixture of several hundreds of components of carbon and hydrogen. Identifying these components is tedious and time-consuming. In addition, weathering alters the composition of a component, which means that the combination of carbon and hydrogen atoms in the oil is changing as weathering takes place. Table 3-2 presents the boiling point of normal alkanes.

Table 3-2: Boiling Points of Normal Alkanes

Alkane	Carbon Atoms	Boiling Point (C°)
Butane	**4**	**0**
Pentane	**5**	**36**
Hexane	**6**	**69**
Heptane	**7**	**98**
Octane	**8**	**126**
Nonane	**9**	**151**
Decane	**10**	**174**

The depth of groundwater in the Mina Abdullah refinery region varies from 25-35 m. Hence, the pollution of groundwater by the direct infiltration of crude oil and hydrocarbons can be ruled out. The only other possible source of groundwater pollution of groundwater is the leaching of pollutants by rainwater and the infiltration of polluted rainwater. As the polluted rainwater infiltrates, some of the pollutants will most likely be adsorbed and retained by the soil in the unsaturated zones before the polluted rainwater reaches the water table. Hence, the study of groundwater pollution requires a good understanding of leaching of the pollutants by rainwater and retention levels of pollutants by soil in the unsaturated zone.

3.7 Solubility and the Soil-Water Partition Coefficient

Water solubility is an important property of organic substances, particularly petroleum hydrocarbons. The solubility in water can range from highly miscible to nearly insoluble. Pollutants that are more soluble have a greater potential mobility in the environment. Table 3-3 presents some of the important properties of selected aromatic and polycyclic aromatic hydrocarbons. One of the important properties is the solubility in water. Benzene is one of the most soluble substances in water. One of the least soluble substances is benzopyrelene.

The soil-water partition coefficient is a measure of the degree to which an organic substance will preferentially dissolve or be adsorbed to the soil. The substance is mixed with equal amounts of water and soil. The coefficient is the ratio of the amount of substance adsorbed to the soil at equilibrium in water:

$$P_{soil\text{-}water} = C_{soil} / C_{water} \qquad [3.1]$$

Where:

$P_{soil\text{-}water}$: Soil-water partition coefficient

C_{soil}: Concentration of oil adsorbed to the soil

C_{water}: Concentration of oil dissolved in water

Table 3-3: Properties of Selected Aromatic and Polycyclic Aromatic Hydrocarbons

Name	Molecular Weight	Solubility in Water (mg/L)	Soil-Water Partition Coeff.
Benzene	78.11	1780	97
Toluene	92.1	500	242
Xylene	106.17	170	363
Ethyl benzene	106.17	150	622
Naphthalene	128.16	31.7	1300
Acenophthylene	154.21	7.4	2580
Acenophthylene	152.2	3.93	3814
Fluorene	166.2	1.98	5835
Fluoranthrene	202	0.275	19000
Phenanthrene	178.23	1.29	23000
Anthracene	178.23	0.073	26000
Pyrene	202.26	0.135	63000
Benzoanthracene	228	0.014	125719
Benzopyrene	252.3	0.014	125719
Chrysene	228.2	0.0038	282185
Benzofluoranthene	252	0.0012	1148497
Benzopyrelene	276	0.00026	1488389
Dibenzathracene	278.35	0.00249	1668800
Benzofluoranthene	252	0.00055	2020971

3.8 Groundwater Sampling and Analysis

To monitor and assess the contaminated groundwater quality, a total of 47 (single and multilevel) wells were drilled in the Mina Abdullah, Mina Al-Ahmadi, and Al-Shuaiba oil refinery regions. The multilevel wells were used to profile the depth of the contaminant in the groundwater. Samples were also collected from existing wells at the Mina Abdullah refinery and from possible surface source sites within the refineries.

During sampling, the field parameters, such as pH, EC, and ORP, were first measured using portable meters supplied with electrodes. Once the parameters stabilised, they were recorded, and samples were collected for laboratory analysis. The samples for hydrocarbon analysis were all collected into amber glass bottles to reduce the effect of organic biodegradation (APHA, 1998). Samples to be analysed for BTEX were collected in 40-ml amber vials, whereas the rest of the samples related to organic parameters were collected in 1-1 amber glass bottles. Samples used to determine the TOC, TPH, and phenol compounds were preserved with 1 ml of concentrated hydrochloric acid (HCl) per litre of sample. Sterilised 1-l glass bottles were used to collect samples for bacterial analysis. Table 3-4 lists the parameters analysed for the water samples by different laboratories.

Table 3-4: Parameters analysed for the collected water samples

Parameter		Method of Analysis
Inorganic	TDS	Standard methods for the examination of water and wastewater
	Major cations (Na, K, Ca, Mg)	
	Major anions (HCO_3, SO_4, Cl, NO_3)	
	Trace elements (As, Cd, Cr, Mo, Ni, Cu, B, Pb, Se, V, Zn, Hg)	
Organic	Toc	
	TPH	
	Phenol	
	BTEX	
	PAHs	
Microbiologic	Total coliforms (TC), Faecal coliforms (FC), Sulphate-reducing bacteria (SRB)	

3.9 Monitoring the design and location of wells

The monitoring wells were installed in the three refinery areas primarily to determine the depth of the groundwater and thus of the water table. To meet this requirement, the monitoring well was designed for multilevel sampling, as shown in Figure 3.1. The location of monitoring wells was selected based on environmental assessments, which identify the source of contaminants in the three refineries. The KNPC study adopted the following guidelines to meet this aim:

- A review of the documented use of the property, including reports, aerial photos, and satellite imagery.
- Walkover of the site to assess present conditions.
- A check for chemical spill residues, die-back of vegetation, and hazardous substance or petroleum products at use and storage facilities (above ground and underground).
- An evaluation of the likelihood of environmental hazards based on the site history.
- A risk evaluation from neighbouring properties.
- An interview with knowledgeable parties regarding the history of the property.

The aforementioned elements adopted to select the location of the monitoring wells were clearly the result of environmental diligence. Model simulation will concentrate on validating the accuracy of its distribution based on the site condition.

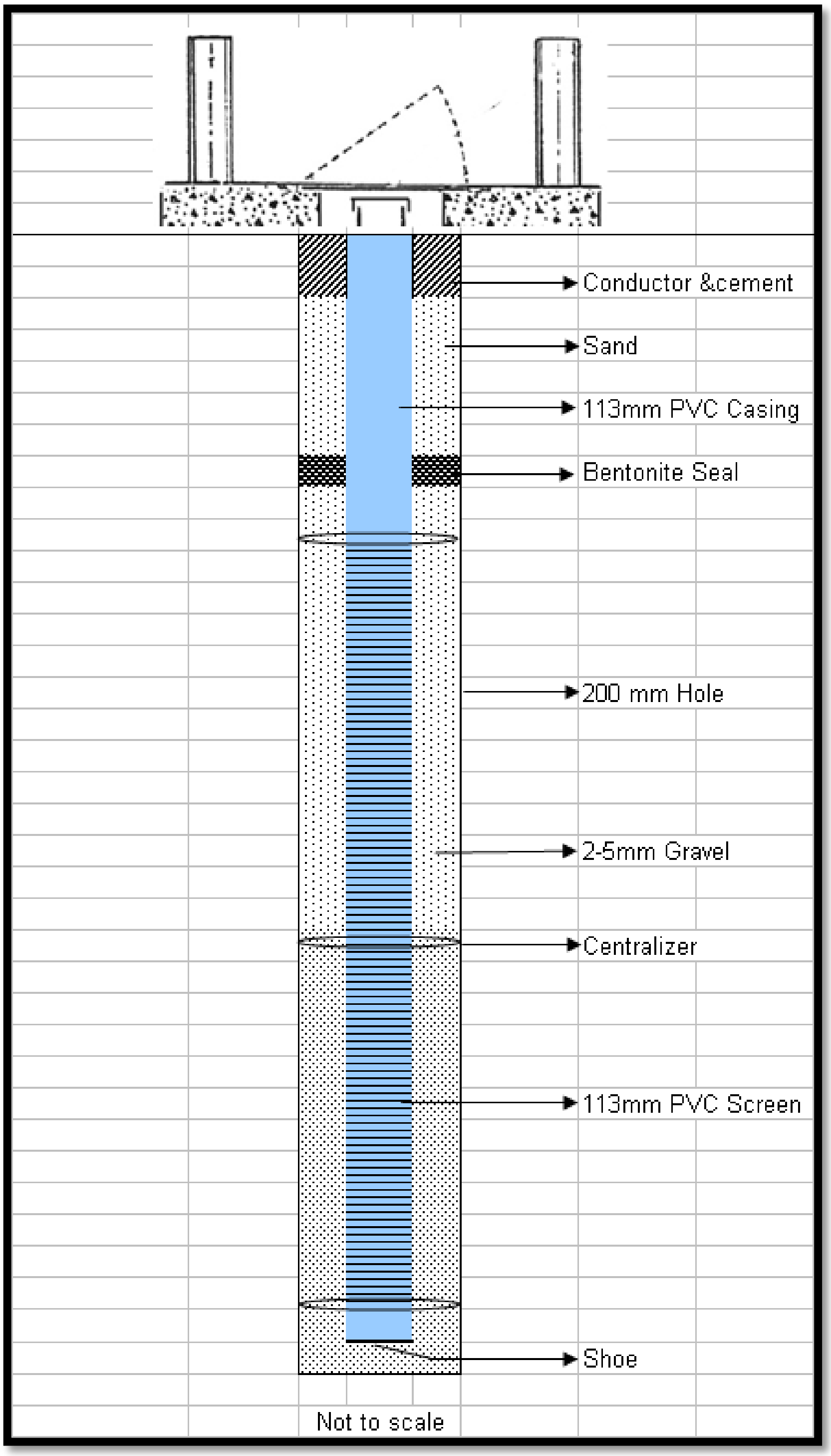


Figure 3.1. General design of the monitoring wells in the study area

3.9 .1 - Mina Al-Ahmadi Refinery

The Mina Al-Ahmadi refinery Figure 4-2 has an approximate surface area of 10.5 km^2 and is located some 40 km south of Kuwait city. Its production rate exceeds 415,000 bbl/d. The surrounding area to the west is the main road (highway to Kuwait city).

Figure 3.2 Mina Al-Ahmadi Refinery

The monitoring network at the Mina Al-Ahmadi refinery consists of 14 wells. All wells, except the MAA-W13 and MAA-W14 wells, are multilevel monitoring wells. Wells MAA-W13 and MAA-W14 were designed to monitor the area and perform pumping tests and can thus be used to measure the water table levels and collect groundwater samples to determine the quality of the groundwater at that location.

Table 3-5 shows the locations of the monitoring wells in terms of their coordinates.

Table 3-5: MAA Refinery Monitoring well locations

Well No	East	North
MAA-1	806558	3219750
MAA-2	806707	3219234
MAA-3	805834	3219593
MAA-4	806648	3217726
MAA-5	805991	3219797
MAA-6	805467	3219559
MAA-7	806572	3219179
MAA-8	806409	3219034
MAA-9	805300	3218713
MAA-10	803723	3218766
MAA-11	803221	3219359
MAA-12	804560	3217714
MAA-13	803259	3217609
MAA-14	803256	3217598

3.9.2 Mina Abdullah Refinery

The Mina Abdullah refinery Figure 4-3 was built on 7.8 km^2 of land. It has a capacity of 240,000 bbl/d and is approximately 48 km south of Kuwait city.

Figure 3.3 Mina Abdullah Refinery (MAB)

The monitoring network of the Mina Abdullah refinery consists of 19 wells; five (MAB-W1, MAB-W2, MAB-W5, MAB-W18, and MAB-W19) are conventional monitoring wells, and 14 are multilevel monitoring wells. Two wells, MAB-W2 and MAB-W18, are dual-purpose wells, i.e., they are designed for pumping tests and monitoring. These two wells are used to measure the water levels and collect groundwater samples. Table 3-6 shows the locations of monitoring wells in terms of their coordinates.

Table 3-6: Locations of the MAB Refinery Monitoring Wells

Well No	East	North
MAB-1	806583	3212272
MAB-2	806667	3211787
MAB-3	806805	3211295
MAB-4	807897	3211079
MAB-5	807320	3211776
MAB-6	807653	3212328
MAB-7	808069	3212677
MAB-8	807908	3213323
MAB-9	807802	3213647
MAB-10	808069	3212677
MAB-11	807908	3213323
MAB-12	807802	3213647
MAB-13	807048	3214103
MAB-14	806495	3214226
MAB-15	805519	3213667
MAB-16	806148	3213217
MAB-17	805858	3213226
MAB-18	806406	3211918

3.9.3 Al-Shuaiba Refinery

The Al-Shuaiba refinery extends over an area of 1.3 km^2 and is located 42 km south of Kuwait City within the Al-Shuaiba industrial area. It has a capacity of 195,000 bbl/d Figure 3.3.

Figure 3.4 Al-Shuaiba Refinery (SHU)

The monitoring network at the Al-Shuaiba refinery consists of 14 monitoring wells (Table 3.3). All monitoring wells, except the SHU-W1 and SHU-W4 wells are multilevel wells. Monitoring well SHU-W1 is located outside the western boundary of the Al-Shuaiba refinery. Monitoring wells SHU-W2, SHU-W3, SHU-W4, and SHU-W5 are within the boundary of the Al-Shuaiba south power station east of the Al-Shuaiba refinery. The conventional monitoring well SHU-W1 and multilevel wells SHU-W6 and SHU-W12 were installed near the fence area. The purpose of these monitoring wells was to understand the hydrogeology of the refineries and their surroundings.

Table 3-7: Location of the SHU Refinery Monitoring Wells

Well no.	East	North
SHU-1	802064	3217915
SHU-2	807484	3215534
SHU-3	806928	3215521
SHU-4	806907	3215800
SHU-5	806862	3216014
SHU-6	806809	3216035
SHU-7	806577	3216015
SHU-8	806439	3215996
SHU-9	806402	3215731
SHU-10	805986	3215496
SHU-11	805176	3215730
SHU-12	804918	3215952
SHU-13	806190	3215995
SHU-14	806375	3215990

CHAPTER 4

COMPUTATIONAL MODELING

4. Computational Modeling

4.1The Study Area

The accumulated pollutants or contaminants from the petroleum plants in Ahamdy Area (refinery , oil lakes , unexpected leaks from the crude oil pipe lines) can be mixed with the water which is used in the utility side like steam generation system or from the API separator pit, forming a hydrocarbon / water mixture . This mixture is considered as the main source of soil pollution.

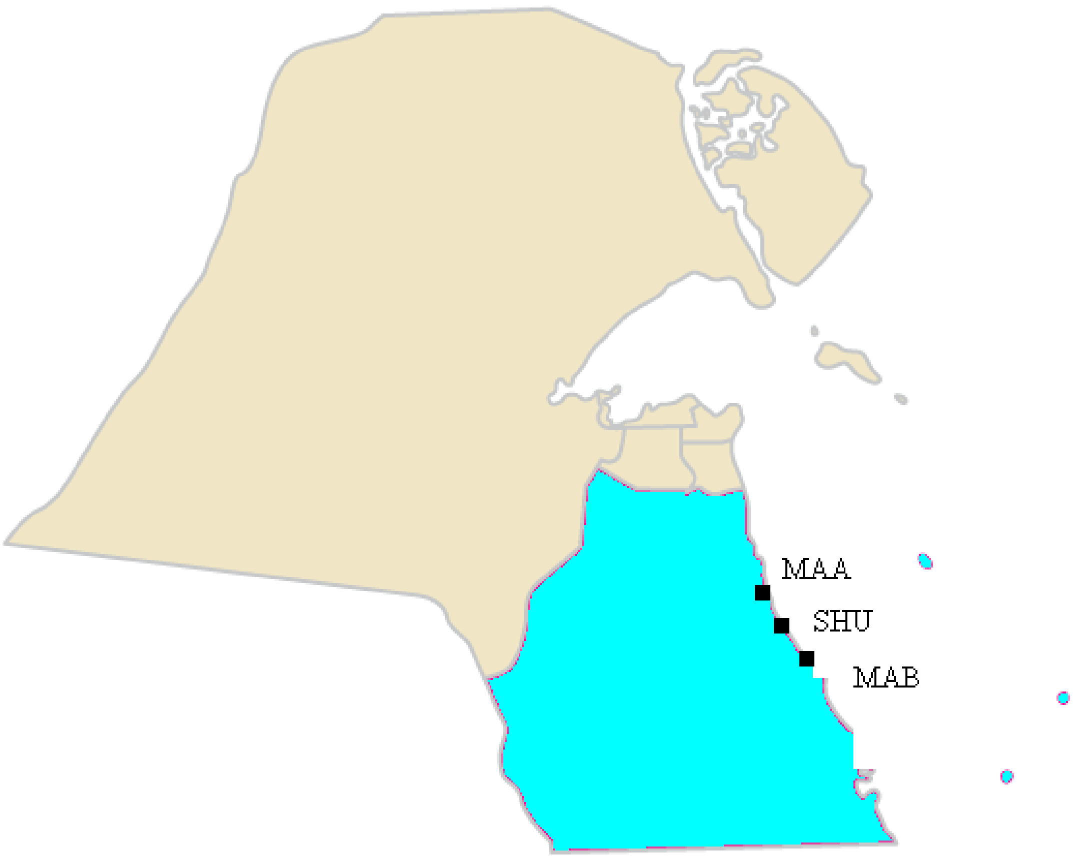


Figure 4.1: Ahamdy Area location

The migration of the polluted mixture through the underground formation of Ahamdy area is a point of concern in the time of new chemical plant is under construction.

Two main projects in Ahamdy Area have been handled by Kuwait National petroleum Company:

- The Clean Fuel Project (CFP); which is considered as a revamp project. needed for environmental requirements to produce a high grade of petroleum products , by installing a new improved desulfuriztion facilities to the old two existing Kuwait Refineries (Mina Al-Ahmady Refinery and Mina Abdullah Refinery) , this project consists of 6 new units in Mina Abdullah Refinery and 9 units in Mina Ahamdy Refinery .

- The New Refinery Project (NRP); this project is considered as the new main project of Kuwait due to its high budget. This refinery is planned to be located at Al- Zour which is at the southern part of Ahamy area .the new refinery consists of 15 units include (CDU , Crude Distillation Unit. FCC unit, fluidized Catalytic Cracker, Coker unit, sulfur recovery plant, ARDs, Hydrogen reformer unit...Etc.).

4.2 Groundwater quality Control

Multilevel analyses of hydrocarbon contaminants in the groundwater at refineries were carried out from January to May 2010. The chemical analysis included the total organic carbon (TOC), total petroleum hydrocarbon (TPH), the BTEX compounds (benzene, toluene, ethylbenzene, and xylene), polycyclic aromatic hydrocarbon (PAH), and phenol content.The COMSOL multiphysics model treated these contaminants as chemical agents with selective boundary conditions. In addition, the salinity of water was expressed as the total dissolved salt (TDS) content. The results obtained by the chemical analysis were compared with the Kuwait EPA (Environment Public Authority) standards for wastewater discharge to the sea, as presented in Table 4-1.

Table 4-1Maximum level allowed for industrial wastewater discharge to the sea

Parameter	Maximum Limits
Aluminium mg/lit	5
Ammonia mg/l	3
Antimony mg/l	1
Arsenic mg/l	0.1
Barium mg/l	2
Beryllium mg/l	0.1
BOD mg/l	30
Boron mg/l	0.75
Cadmium mg/l	0.01
Chlorine mg/l	0.5
Chromium mg/l	0.2
Cobalt mg/l	0.2
COD mg/l	200
Colour	Free from contaminants
Copper mg/l	0.2
Cyanide mg/l	0.1
Dissolved Oxygen mg/l	less than 2
Floatables mg/l	None
Fluorides mg/l	25
Iron mg/l	5

Lead mg/l	0.5
Lithium mg/l	2.5
Manganese mg/l	0.2
Mercury mg/l	0.001
Molybdenum mg/l	0.01
Nickel mg/l	0.2
Nitrate mg/l	30
Oil/Grease mg/l	10
Organic Nitrogen mg/l	5
Pesticide mg/l	0
pH	8
Phosphate mg/l	2
Silver mg/l	0.1
Sulphide mg/l	0.5
Temperature °C	10
Total Coliform Bacteria (MPN/100 ml)	1000
Total Nitrogen mg/l	30
Total Recoverable Phenol mg/l	1
Total Soluble Solids mg/l	1500
Total Suspended Solid (TSS) mg/l	10
Turbidity NTU	50
Vanadium mg/l	0.1
Zinc mg/l	2

4.3 Individual site model and analysis

The Kuwait refineries considered a major source of pollution and harmful wastes. unexpected off shutdown , poor maintenance , faulty equipment, losing of environmental controls, leakage from tankage area (tank farm) etc. may have significant impact on the local refineries resulting in less than optimal system performance. If the refinery operation is poorly operated or compromised, the release of pollutants to the local environment may result high amounts of pollutants.

Approximtly 47 montiring wells were drilled across the KNPC three refineries and these were uesed to establish agroundwater montiering network comprising of 14 montiring wells at Mina Al-ahamdy refinery , 18 montiring wells at Mina Abdullah Refinery and 13 montiring wells at AlShuaiba Refinery .

The monitoring wells have been drilled to assesst the groundwater quility in the Ahamdy area. The environemntal department has identified the potential source of contamination records in view of historic environmental incidents. The location of monitoring wells has been selected based on Environmental assessment which identify the source of contaminants in the three refineries . The KNPC study includes the following as a guide lines adopted to meet this aim:

- A review of the documented use of the property including reports, aerial photos, and satellite imagery.
- A walkover of the site to assess present conditions.
- Check for chemical spill residues, die-back of vegetation, and use and storage facilities (above the ground and under the ground) for hazardous substance or petroleum products.

Based on the aforemention elements the location of each monitoring well is selected to cover the most suspected contaminated region. One of the important keys of understanding any ground water pollutants is to identify the source of pollution. The distribution and the nature of pollutants in the surface and subsurface regions determine the paths that the pollutants follow towards the water table levels. In case of hydrocarbon pollutants the distribution and nature of pollutants change with time because of weathering and biodegradationoneof the important tasks of any groundwater pollution study is to identify the source of pollution. Vast area of the ground surface were polluted by the oil refinery operations resulting in hydrocarbons leaks or .seven distinct source of pollution can be identified:

1. Crude oil that accumulated in the oil lakes.
2. Hydrocarbons spilled from product storage tank.
3. Seawater used for firefighting system or used for cooling process.
4. Subsurface leaking upstream or downstream pipe.
5. Large volumes of product of combustion into the atmosphere.
6. Oil refinery waste water.
7. API oil separator.

At the ground surface , the main source of contamination are the oil leaks , contaminated water from fire-fighting and flue gas from the stacks (FCC stack) and flares system .the other form of pollution is from leakage from damaged storage tanks. The movement of oil contaminants through unsaturated zones and aquifer units are largely controlled by geological, hydrological and groundwater flow conditions. The presence of high permeable zone would assist rapid movement of contamination. On the other hand, the high dense zone will inhibit the movement of contaminants. In this regards the better understanding of the mechanism of local regional settings is essential.

The source of contaminated water in Ahamdy Area :

At Kuwait refineries numbers of contamination sources were identified most of them involved hydrocarbon contamination. They are differs in its impcat on groundwater quility . as an example of some sites of contaminats for each refinery has been identified as follows :

4.3. 1- Mina AlAhmaidy Refinery contaminated sites

- *The disentrainment flash basin* ;these are concrete basins used to separate the oily water from the sea water which has been used for cooling process . the dimentions of the two basins are 139 m X 120m X 3m and 139m X 25m X 3m respectivily .

- *The sea water lagoon (cooling sea water return)* ; is a concrete basin connected by underground cannel to the main flash basins , the function of the lagoon is to separate the oily wate water from the waste water generated in the refinery before discharging the the water back to sea . the usual inspection round shows that the wall suffer from various degree of cracking which alllow the waste water to slip through the underground surface . a monitoring well was selected at a location down gradient from the lagoon to assess leakages to the groundwater .

- *The old refinery area ;* the visual inspection of the site indicated that the soil is contaminated with hydrocarbons . the site is about 220m from the seashore where the water table is shallow , and could quite possibly be contaminated by the hydrocarbons. Two monitoring wells were installed at the site .

- *Spills from tankage area ;* the soil at the site of the tank is contaminated with hydrocarbons . the inspection report shows that the source of contamination is a hydrocarbon spill from the tank .

- *The spent catalyst yard area ;* the storage yard located at the southern part of the refinery . it is an open area occuping approximately 24,200m2 . the spent catalyst was stored in metal drums : however , it is very likely that some of the drum may have suffered corrsion in such an open yard located on the coast, and as a result some spent catalyst may have leaked to the soil . the yard is now used as agas filling station with surface fuel storage tank . theground surface of the gas station is paved with asphalt .

- *Old gas filling station :* this site was identified by KNPC environmental department . this site is an underground storage tank of gasoline which has been built 30 years ago . maintenance records shows that the metal of this tank was suffered from corrosion and continous cracking . the insepction shows that the leak might be found nearby the area .

Table 4-2 present the measured values of the water table below the ground water surface , the water table level above the mean sea level , and the surveyed ground surface elevation at the 14 monitoring well. The minimum values in meter of water table below the ground surface are 0.97,1.64,0.97,1.32,1.56,2.3 and 2.76. at well MAA-W1, MAA-W3, MAA-W5, MAA-W7, MAA-W8 and MAA-W4.

Table 4-2: Location of the MAA refinery monitoring wells

Well No	East	North	Ground surface elevation(m)	Water level (mbgl)
MAA-1	806558	3219750	2.1	1.8
MAA-2	806707	3219234	4.3	2.8
MAA-3	805834	3219593	9	1.6
MAA-4	806648	3217726	4.4	3.3
MAA-5	805991	3219797	7.5	1.06
MAA-6	805467	3219559	11.18	1.75
MAA-7	806572	3219179	7.131	1.6
MAA-8	806409	3219034	8.53	2.3
MAA-9	805300	3218713	17.2	5.62
MAA-10	803723	3218766	31.5	13.6
MAA-11	803221	3219359	40.7	14
MAA-12	804560	3217714	21.97	8.55
MAA-13	803259	3217609	37.95	12.17
MAA-14	803256	3217598	38.6	12.54

The distrubtion of the monitoring wells in Mina Al-Ahamdy Refiney can be shown in Figure 4-2 .The red squares represent the values of water table at the seashore.as mensioned previosly, the distribution of the wells was not desgined for the representation of the water table.variation in water depth and therefore, the water table map based on the data from these wells may not be exactly representive.

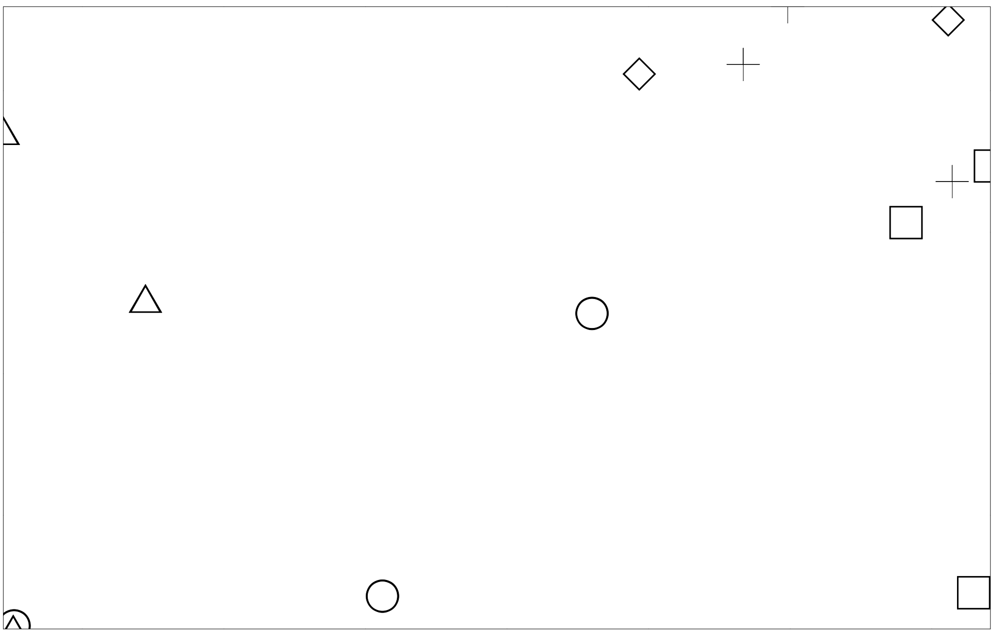


Figure 4.2 Montoiring wells locations in Mina Al-Ahamdy

Figure 4.2 present the simulated water table depth below the ground surface . The simulated map indicates a source of water recharge MAA-W6 and MAA-W5 located near the lagoon. The map shows that the deep water table at the east side of the refinery.

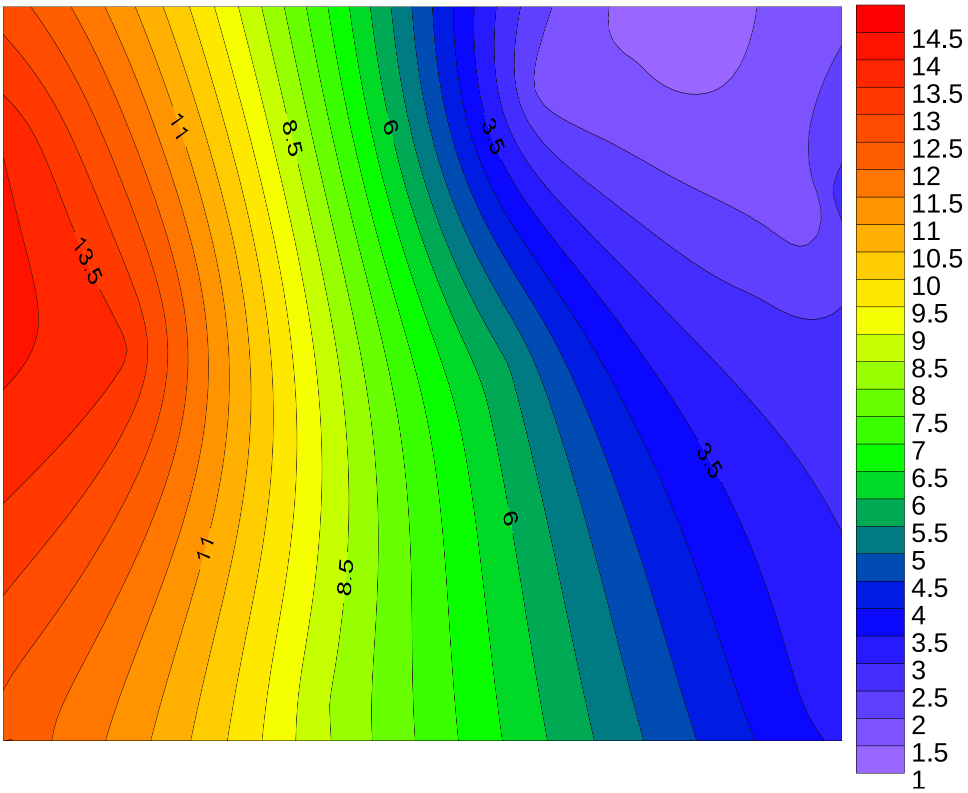


Figure 4.3 water level in the MAA refinery

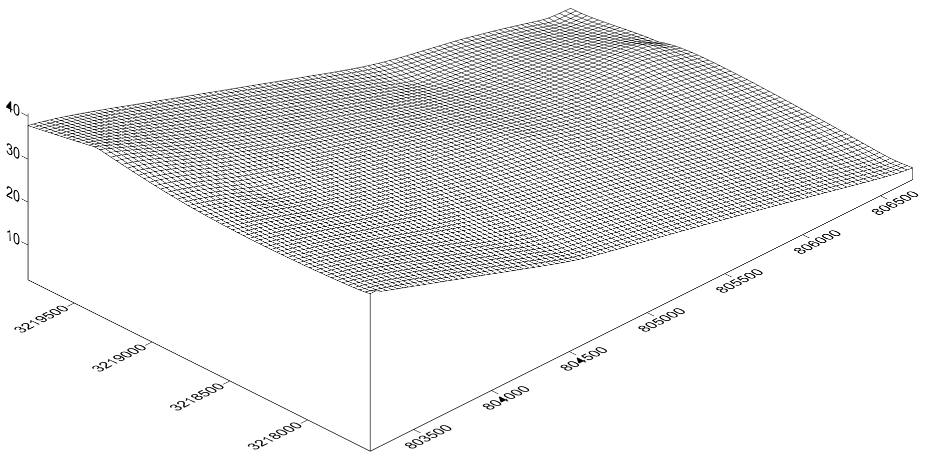


Figure 4.4 underground water level in the MAA

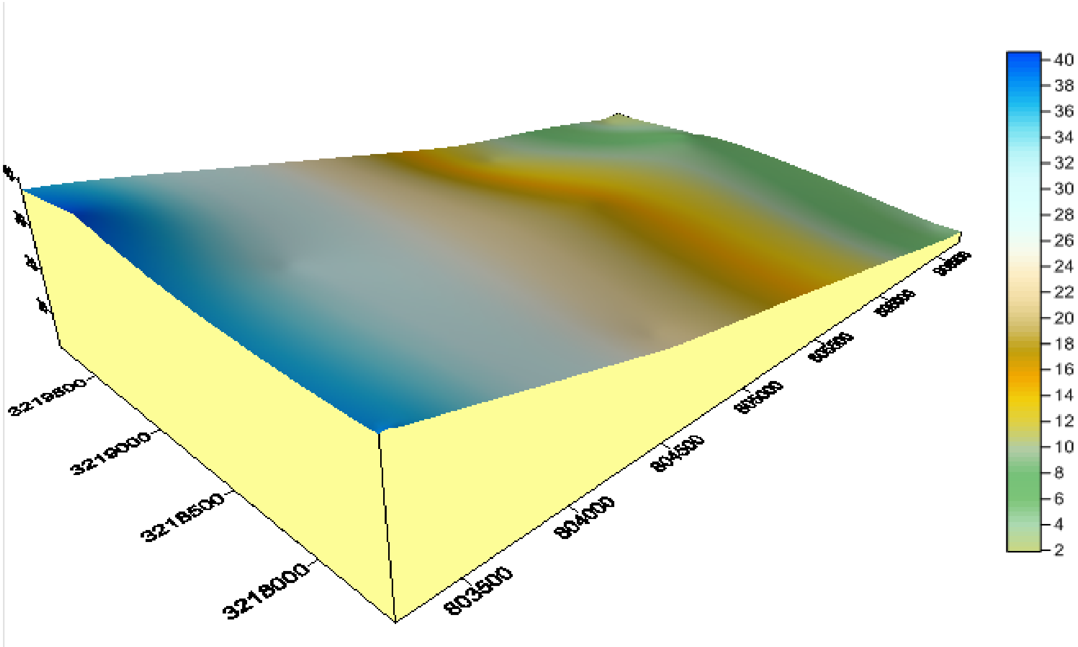


Figure 4.5underground water level in the MAA refinery in 3-D

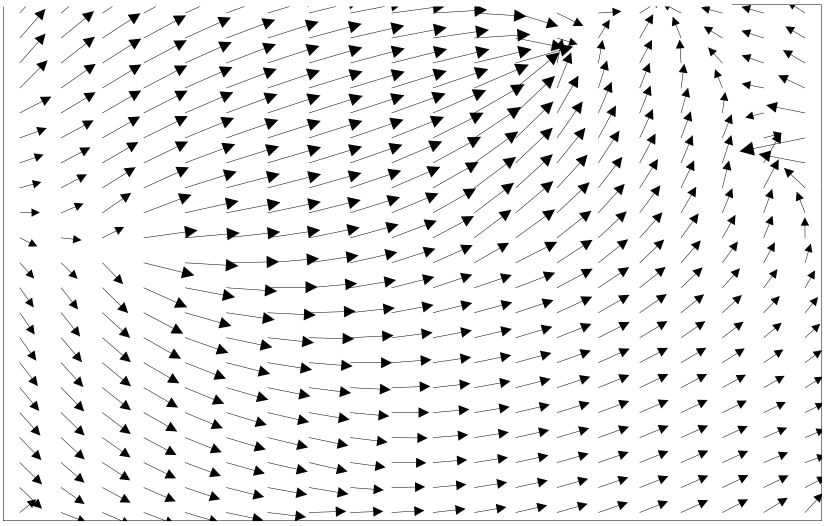


Figure 4.6: Mina Al-ahamdy A Refinery groundwater flow

The simulated map of the water table level above the mean sea level at the Mina Al-Ahmadi refinery site is given in Figure 5-5. The green colour represents the coastline. The figure shows that the water table at the refinery follows the general trend of flow in Kuwait. The map does not show any major or local source of recharge at the refinery site or outside the refinery. The flow direction of underground regimes does not differ significantly from those of the Mina Ahamdi refinery as described in Figure 5-6.

4.3.2- Mina Shuaiba Refinery contaminated site :

At Al- Shuaiba refienery five site of contamination were identified as a source of hydrocarbon contamination . no source of spent catalyst at the refinery . becuase these were transpoted to the other two refineries . the five sites are ;

- *The API basin :* this is concrete basin with the dimensions 40m X 30mX 2m . located at the northeastern corner of the refinery , the API basin function is to chemically separate the different hydrocarbon wastes from the effluent water coming from the cleaning of the refining units . the basin is usually maintained every five years , the last of which was in 2007 . the floor of the basin was contaminated with black hydrocarbon sludge . suchcondition .

- *The hydrocarbon sump :* this is a concrete underground storage unit used to store wastewater contaminated with different hydrocarbons or the slop oil . this is adjacent to the API basin . this sump collects effluent water from the floor cleaning in the refining units . this pit is maintained every five years . a hand dug pit near the sump and the API basin by KNPC revealed that the water table is heavly contaminated with free product . it was also noticed that part of the sump is below the water table .

- *The draingae canal ;* this is a concrete drain discharge waste water used in floor cleaning of the refining units to the sump . the drainage canal may be a threat due to contaminated water leaking from the cracks in the walls or base .

- *The slop oil pit;* there are two small pits built of concrete and located between the slop tanks .the first pit , is the slop oil pump pit , with dimensions of 3.5m X 3m X 0.5 . the second pit is also the slop oil pit , which collects water from the tanks and discharges the contaminated water to the API . its dimensions are 6.5m X 4.2m X0.5 . the condition of the basin suggests that is a possible source of local contamination for the soil and probably for groundwater .

- *The maintenance yard ;* this is a possible source of contamination from spilling during maintenance operations . it is also possible that waste may leak from an open trench nearby .

Table 4-3: Location of the SHU refinery

Well no	East	North	Ground surface elevation(m	Water level (mbgl)
SHU-1	802064	3217915		3.2
SHU-2	807484	3215534	3.2	3.3
SHU-3	806928	3215521	9.1	4.45
SHU-4	806907	3215800	6.4	6.4
SHU-5	806862	3216014		6.66
SHU-6	806809	3216035	7.6	2
SHU-7	806577	3216015	14	5.18
SHU-8	806439	3215996	17	6.7
SHU-9	806402	3215731	18.5	7
SHU-10	805986	3215496	22.24	7.75
SHU-11	805176	3215730	28.36	11
SHU-12	804918	3215952	30.99	16.64
SHU-13	806190	3215995		8.36
SHU-14	806375	3215990		7.03

In the Al-Shuaiba Refinery and the Desalination plant , 13 monitoring wells were aimed to measure the contamination of the monitoring wells. Figure 4-7 shows the distribution of monitoring well location throgh Al-Shuaiba refinery plot,the sold square are water table levels near the seashore except two squares which are at the location of well W1 and W4 at the eastern, and western borders of the Desalination Plant, respectivily.

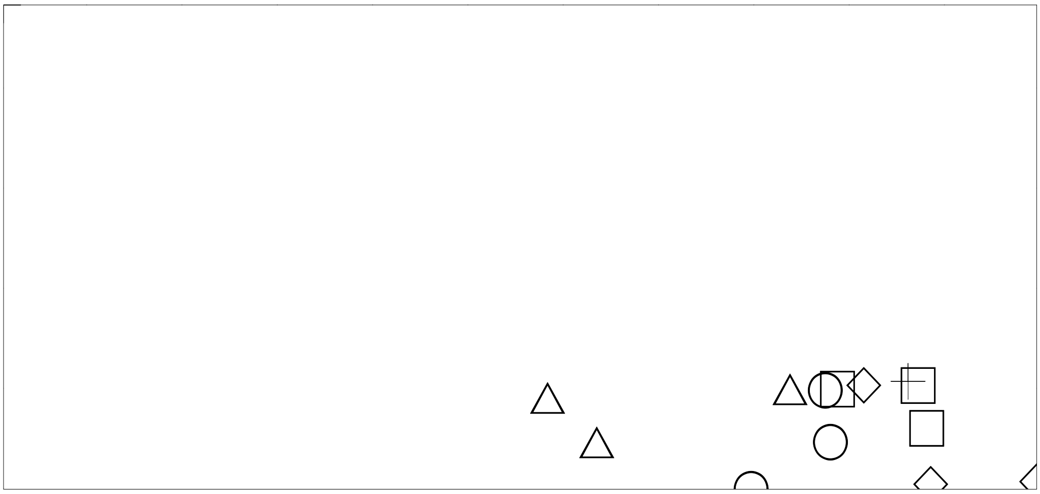


Figure 4.7 : Montoiring wells locations in SHU

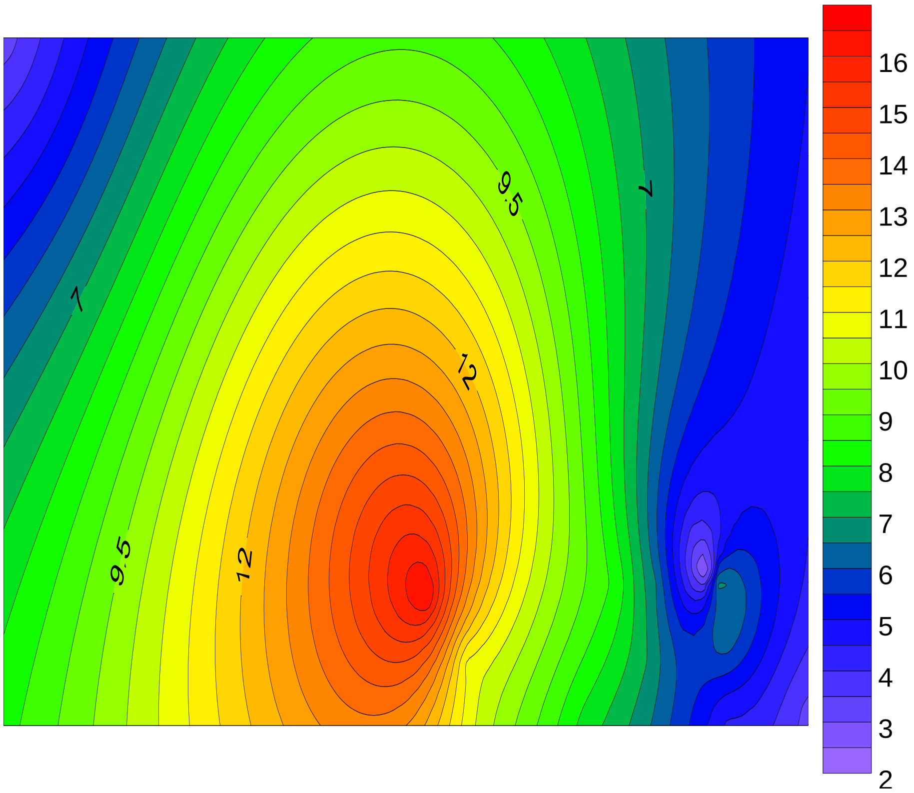


Figure 4.8 The water level in the SHU refinery

Figure 4.8 presents the simulated water table depth below the ground surface. The map shows that water table contour nearby the API area indicates that there is a source of water recharge at the subject area.

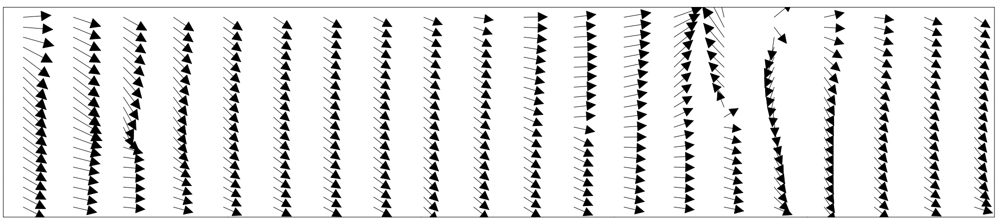


Figure 4.9: SHU Refinery groundwater flow direction

Figure 4.9 shows the direction of underground water flow direction which proofs the concluded pathway from west to east (at sea discharge).

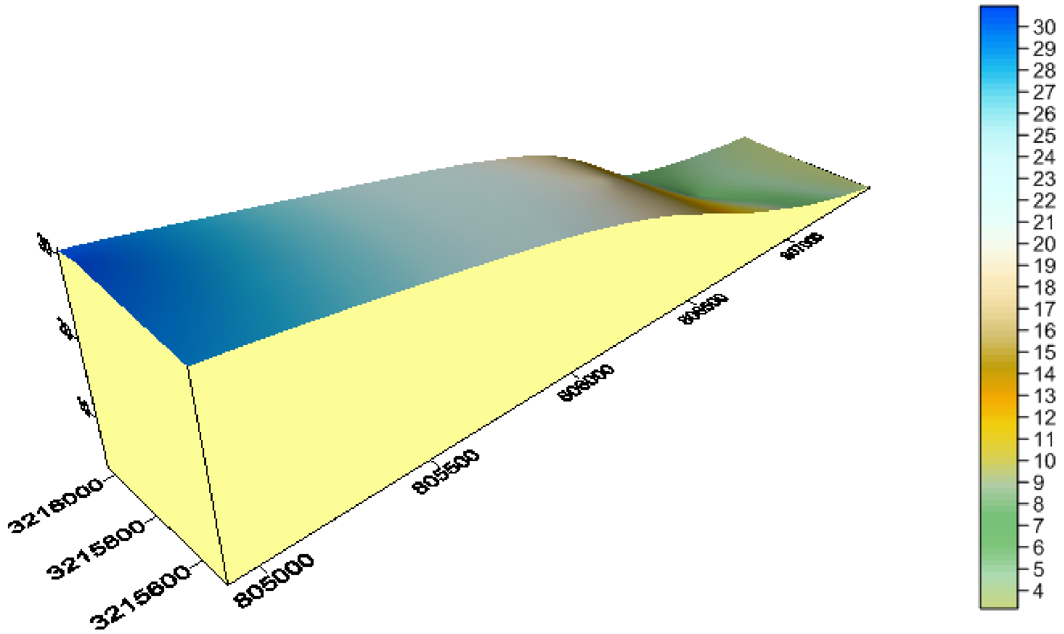


Figure 4.10 the water level in the SHU refinery in 3-D

4.3.3 Mina Abdullah Refinery Contaminated sites

At Mina Abdullah Refinery , five sites were discovered as a source of zones of contamination for groundwater . these sources are the crude oil pit , The south retention basin , The arsenic site spent catalyst storage yard , Fuel filling yard , Deep oil wells and The spent catalyst yard.

- <u>*The crude oil pit*</u> : this is an old pit in the ground with no lining or any sort of sealing . It has a radius of 6 m , and the approximate depth to the top of the hydrocarbon waste is 1.0 m from the surface . the inspection group discoved that some hydrocarbons still present in a thick and heavy liquid phase . the condition of the contaminat at the openpit indicates that the light oil product may have evaporated .

- *The south retention basin ;* this basin is adjacent to the mixing basin and its dimentions are 60m X 28m X 1m . the design of this basin is similar to Noth retension basin in Mina Al-Ahamdy refinery . the basin base was impacted by different degrees of cracking which may have caused leakage prior to the onset of maintenance activites .

- *The arsenic site spent catalyst storage yard;* this is a fenced site where arsenic used to be disposed of in aground pit . which is covered by natural dirt cover .

- *Fuel filling yard ;* this yard has above ground storage tank . the site was observed during the time of inspection of the contamination zoneat the refinery . the site iscontaminated with hydrocarbon that leak during the filing of tanks . the site may be a source zone of soil and groundwater contamination . a monitoring well has been installed down gradient of this site .

- *Deep oil wells (old):* KNPC drilled 11 wells during 1990 at different location of MAB refinery . the wells were drilled to a depth of 30m . Neither the purpose nor the design of the wells is clear . these wells may cause cross contamination between diferent stratigraphic layers if they contaminated .

- *The spent catalyst yard area ;* the storage yard located at theeast of the refinery it is very likely that some of the drum may have suffered corrsion in such an open yard located on the coast, and as a result some spent catalyst may have leaked to the soil .

Table 4-4:presents the measured values of the water table belwo the ground surface , the surveyed ground surface elevation at the monitoring well loaction at Mina Abdullah Refinery.The minimum value of water table belwo grounf surface is 1.95 m at MAB-W8 which is located at the east side of the Refinery toward

Table 4-4: Location of the MAB refinery

Well No	East	North	Ground surface elevation(m)	Water level (mbgl)
MAB-1	806583	3212272	25.61	9.65
MAB-2	806667	3211787	26.96	11.9
MAB-3	806805	3211295	26.43	12.8
MAB-4	807897	3211079	10.35	4.55
MAB-5	807320	3211776	18.61	7.26
MAB-6	807653	3212328	11.79	7
MAB-7	808069	3212677	5.89	3.5
MAB-8	807908	3213323	4.51	1.9
MAB-9	807802	3213647	4.93	2.35
MAB-10	808069	3212677	4.96	2.22
MAB-11	807908	3213323	12.04	7.9
MAB-12	807802	3213647	11.36	7.2
MAB-13	807048	3214103	14.90	9
MAB-14	806495	3214226	22.61	15
MAB-15	805519	3213667	36.18	22.7
MAB-16	806148	3213217	30.16	19.75
MAB-17	805858	3213226	33.02	17.17
MAB-18	806406	3211918	29.89	13.4

The location of measured points at Mina Abdullah refinery are presented in Figure4-4, which aslo displays the locations of wells at the seashore where the water table os zero above the mean sea levels.At this refinery , 19 measuring points were constructed where two of them where clsoe to each other W2 and W19.

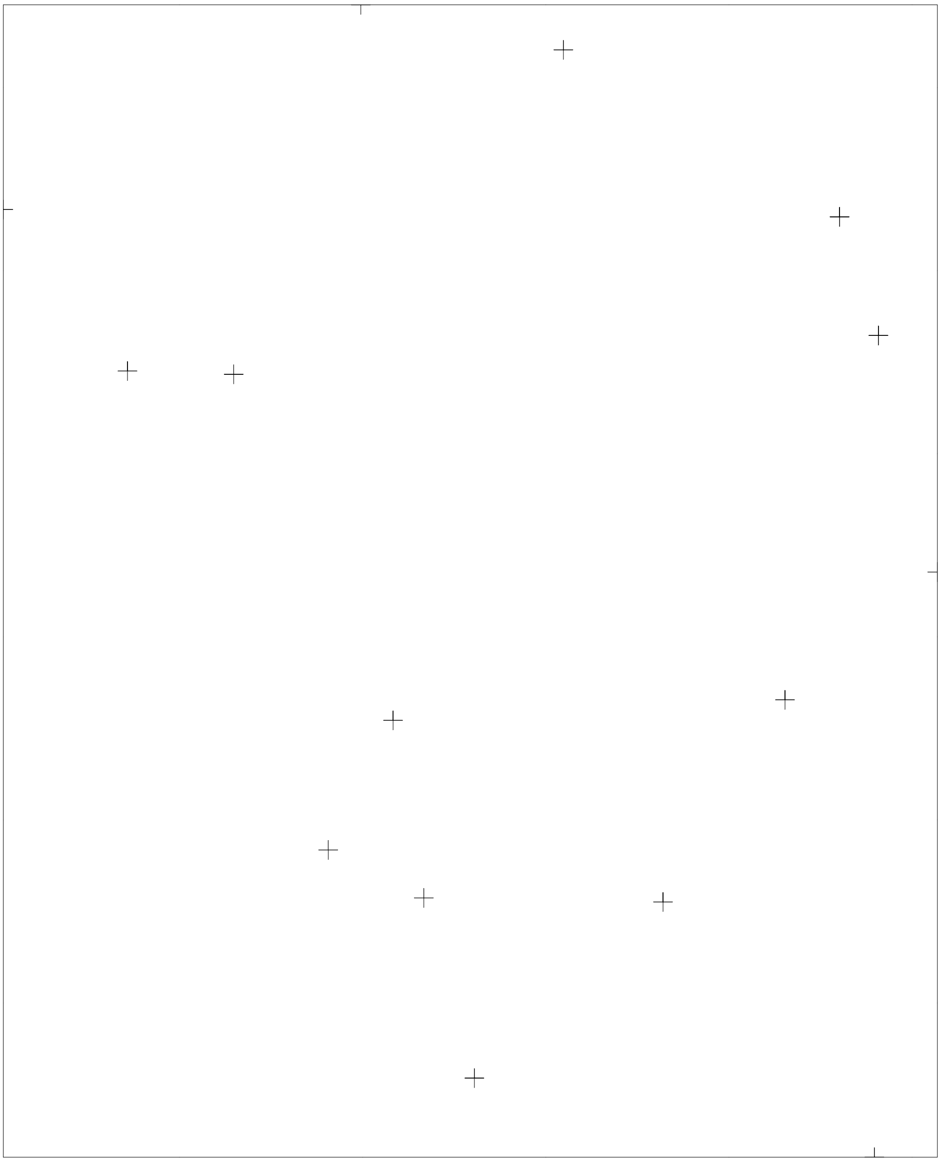


Figure 4-11. Montoiring wells locations in Mina Abdullah Refinery

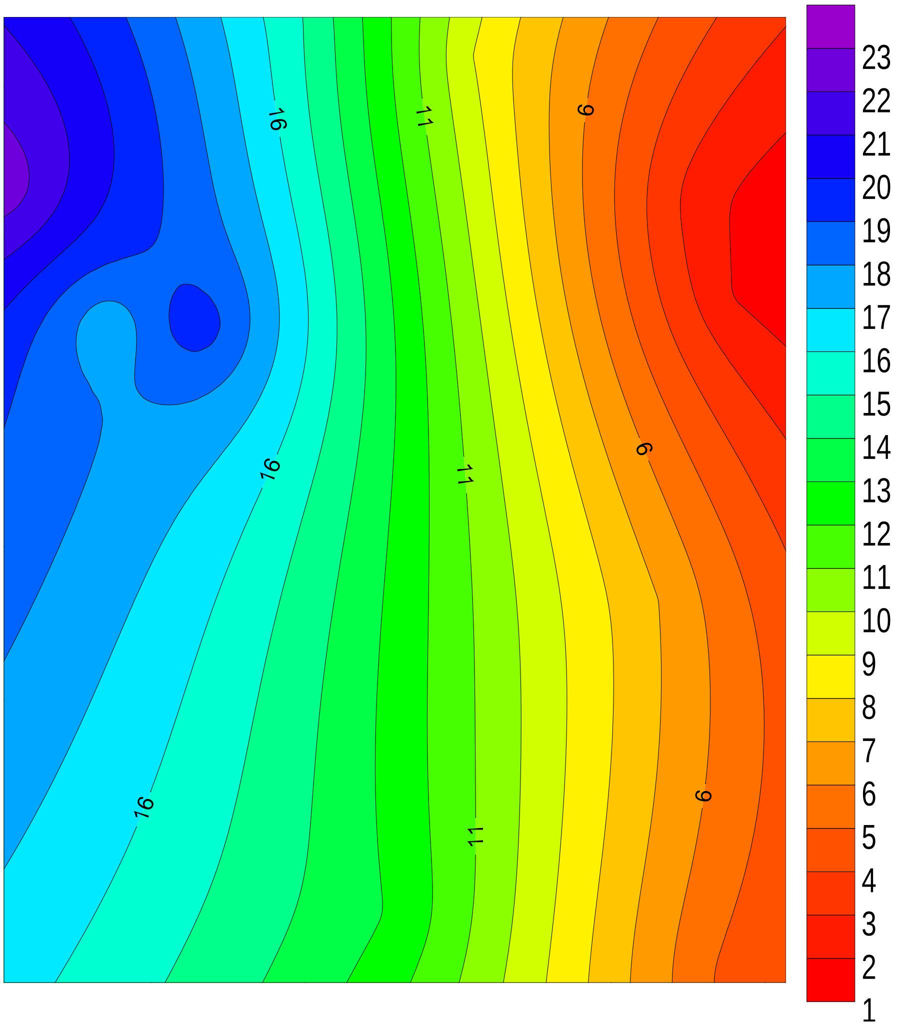


Figure 4.12 The water level in MAB refinery underground region

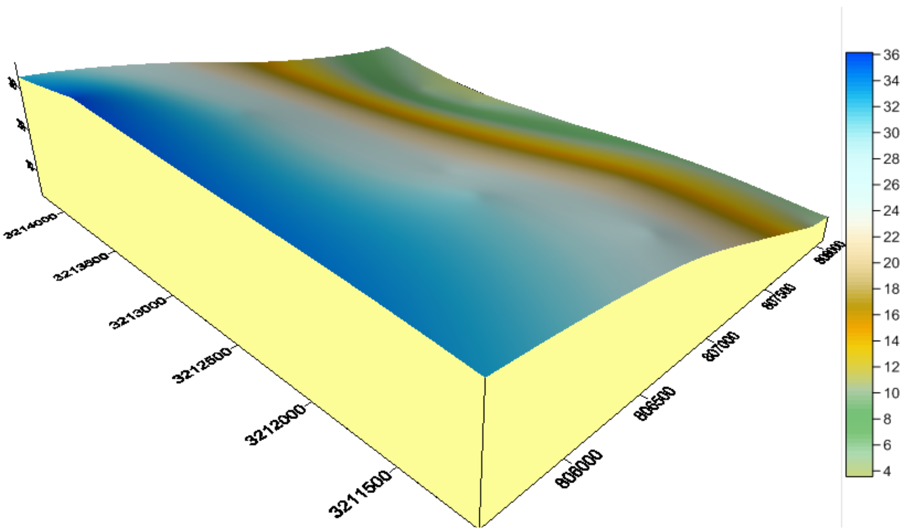


Figure 4.13 The water level in MAB refinery underground region in 3-D

4.4 Numerical Modeling

4.4.1 Modeling objectives

In this study, a groundwater flow model will be introduced using COMSOL Multiphysics, FEMLAB which indicated that it is very useful to solve such a problem.

The objectives of the modeling work is to identify the main aquifer type(s), build a 3-D numerical model for the aquifer underlying the refineries using available field information, delineate and characterize the contamination plume and help develop a plan for the remediation of the aquifer and prevention of further pollution in the future. The modeling work described in this study constitutes an initial quantitative assessment of the hydrogeologic conditions at the three sites. It accompanied a sustained site investigation campaign and that included the installation of a series of multilevel monitoring wells and other observation boreholes.

The objectives of the study was to analyze available drilling data, develop a conceptual geologic and hydrogeological model, build and calibrate the numerical model, set the appropriate guide lines for performing a pump and treat scenarios and run a hypothetical plume simulation to estimate the shape and speed of its spread.

Review of drilling data results and sieve analysis revealed the presence of predominantly sandy aquifer across the study area. A west to east flow regime was identified and delineated with constant head boundary conditions at the western and eastern boundaries and by no flow conditions in the north and south. A3-Dimentional numerical model was build using FEMLAB. The aim was to gain understanding of the hydrodynamic conditions based on available field information. The hydrodynamic model was then used for assessing remediation scenarios and transport simulations.

4.4.2 Modeling strategy

One of the primary challenges in developing a realistic groundwater flow model for the analysis of the effects of pollution is obtaining valid boundary conditions. The domain boundary of the model need to be extended sufficiently far away from the main zones of concern within the study area to avoid the effects of the approximated boundary conditions on the solution. Ideally, every system should be extended to the physical system boundaries. However, this si often not practical because in order to simulate regional flow systems, the desired level of discretization in the study area cannot be extended over the whole region due to computational constraints and to a lack of detailed data in the areas far from the area of interest. Optimal boundary extent were chosen for the current model, ensuring minimal effects of the boundaries on the solution.

4.4.3 Conceptual Geologic Model

The conceptual model in this study considered the geometry underlying Ahamdy area which consists of the three refineries. The monitoring well location and its data are the main components to define the model geometry. Figure 4.14 indicate the monitoring well location in term of coordinates in the whole area of study, Figure 4.15 shows underground water level at the Ahmadi site.

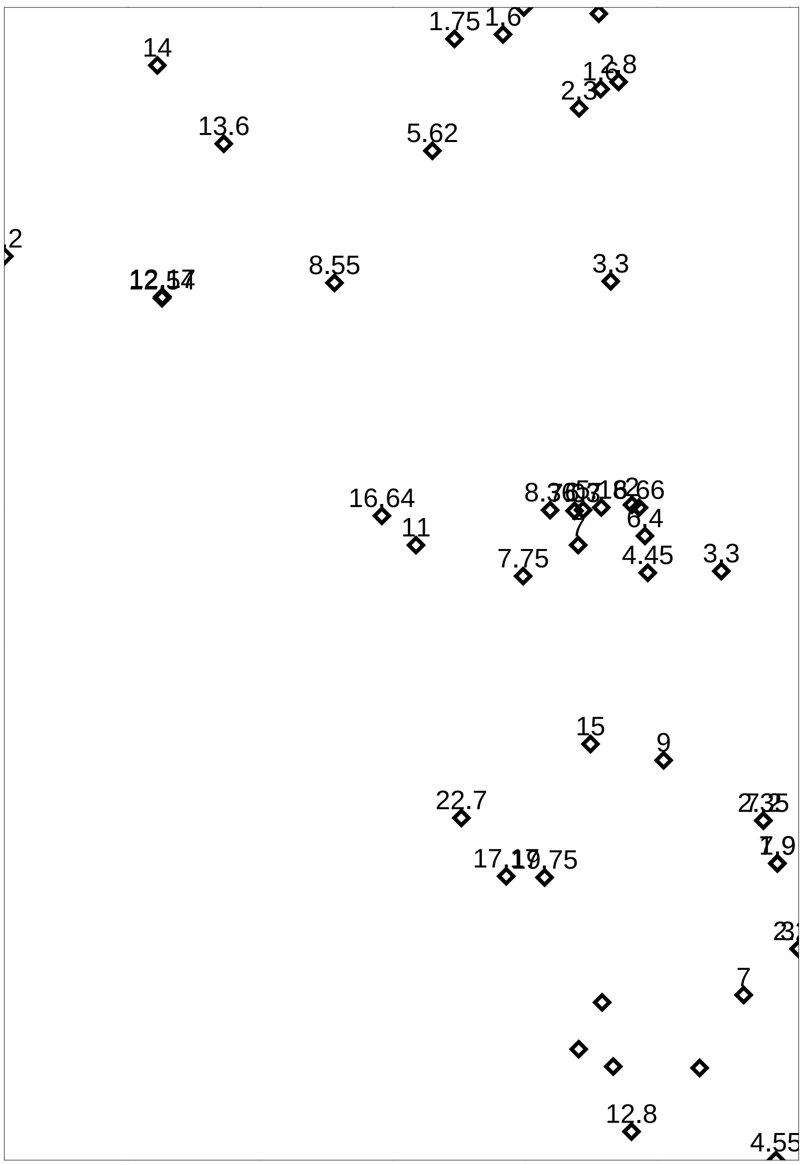


Figure 4.14:Montioring wells locations in the whole Area of Ahamdy study

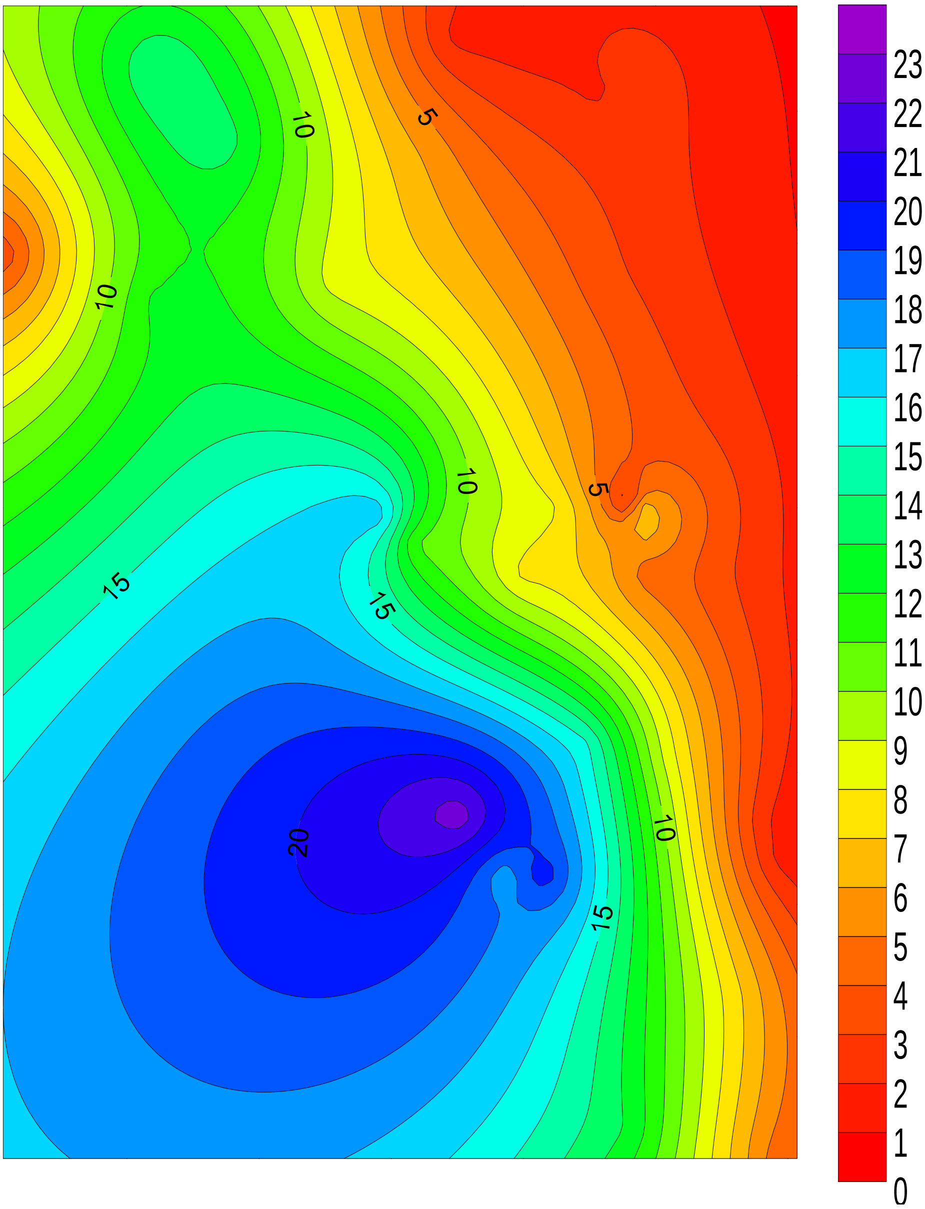


Figure 4.15 The underground water level at the Ahmadi site

The conceptual geological model across the study area figure 4.16 can thus be described as a 35 m deep formation, approximately 10 km long and with an approximate width of 8 km with relatively high permeability as one aquifer with sand layer.

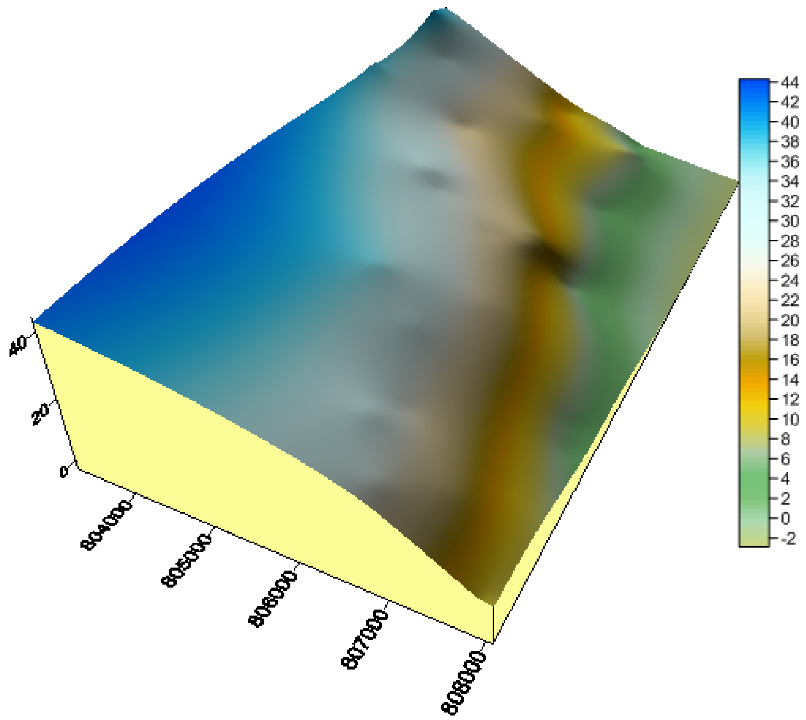


Figure 4.16: 3-D Model of the Ahmadi underground water level

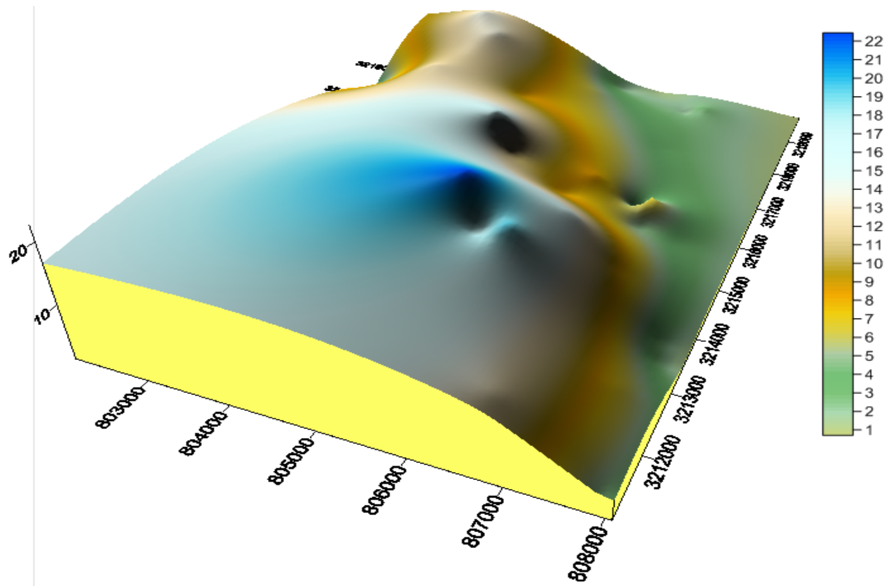


Figure 4-17: 3-D Model of the Ahmadi underground water level

Water level in the observation wells were interpolated to develop a water level contour map figure.4.18. Based on the contours generated, it is possible to see the regional direction of flow in the study area, which confirms the west to east flow. A gentle hydraulic gradient was estimated (between 3 to 4m/km from). Recharges take place mainly from lateral inflow, and to a lesser extent from precipitation events. The Arabian Gulf constitutes the only natural discharge from the system.

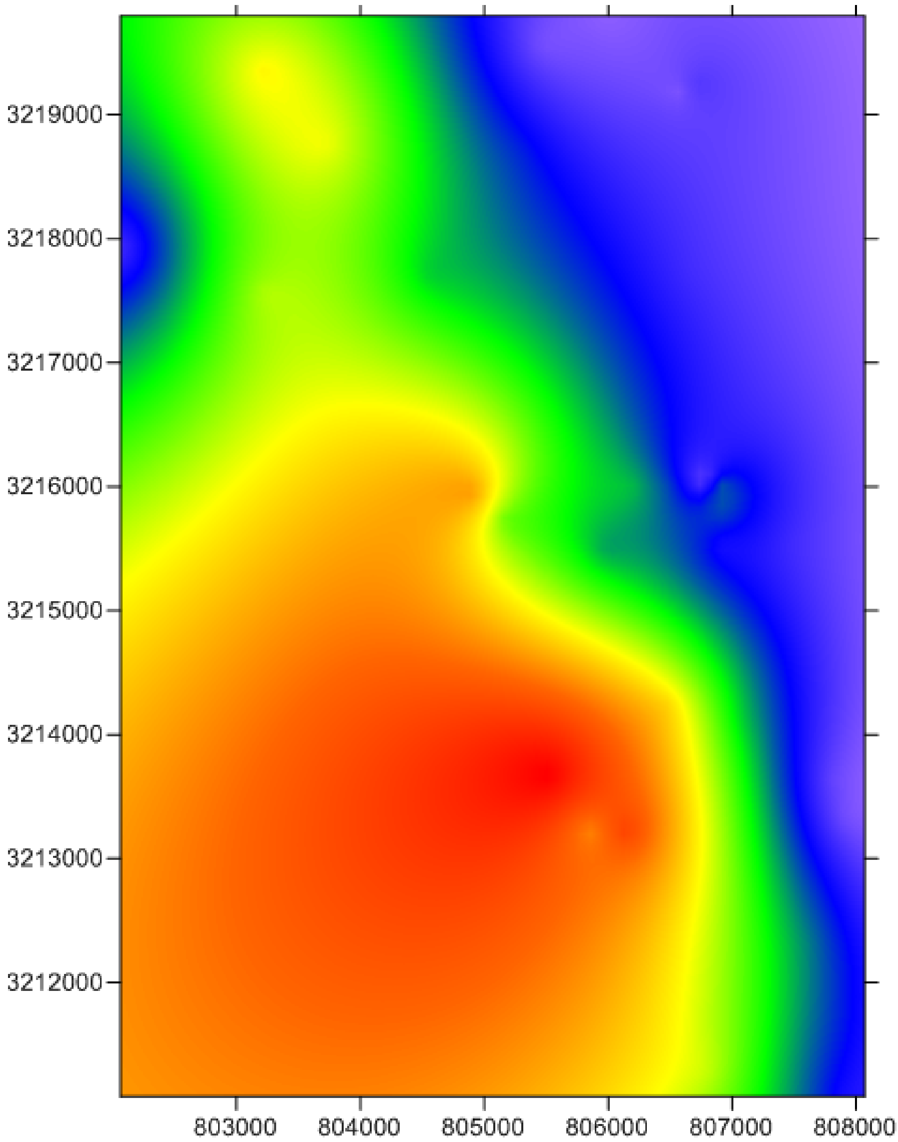
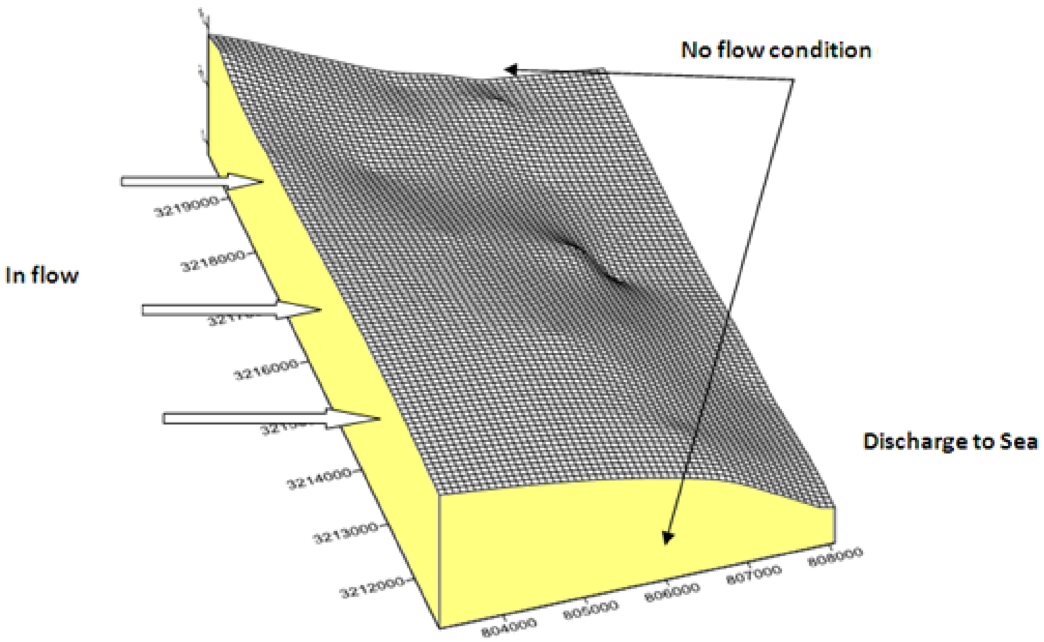


Figure.4.18. Heights of water table within the study area in Ahmady

4.5 Building the Model

The aquifer underlying the three refineries can be represented by a rectangular sedimentary basin isolated on two sides (north and south) by no flow (symmetry) boundary. The western boundary constitutes the lateral inflow boundary while the eastern boundary (Arabian Gulf) constitutes the discharge boundary of the system. Although the lower limit of the aquifer was not reached by the drilled wells, the nature of the problem at hand is shallow by nature, and is unlikely to be affected by the depth limitation.



Conceptual models are used to describe the components of the ground water flow system and their relationship to the overall flow regime in the aquifer (Fig.4-19Fig.4-20,Fig.4-21) shows the chosen cross section of selected wells MAB-W3,MAB-W6,MAB-W7,MAB-W12. Which gently dipping toward the sea in line with trend described previously.

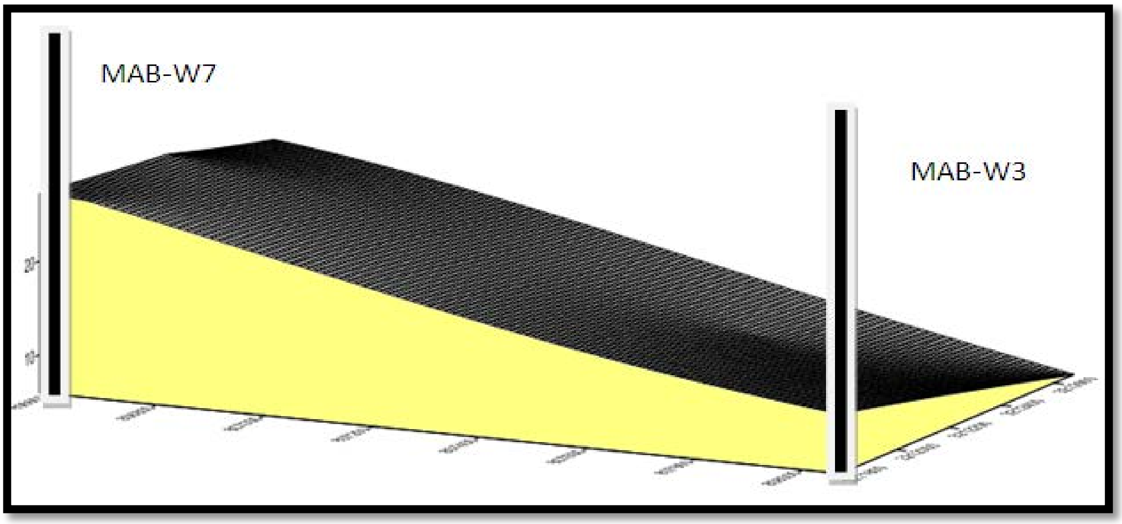


Figure 4.19 Cross sectional view of MABW7-MABW3

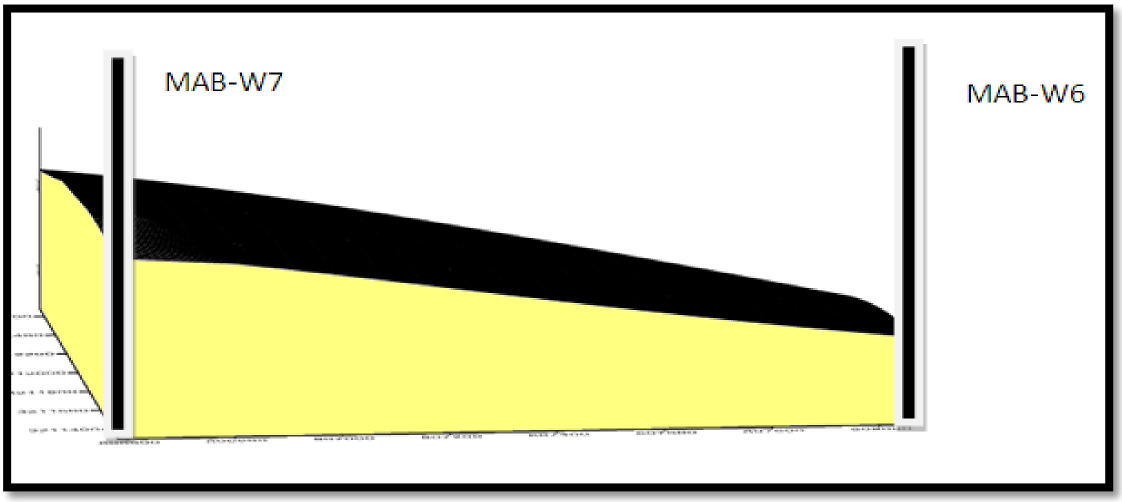


Figure 4.20 Cross sectional view of MABW7-MABW6

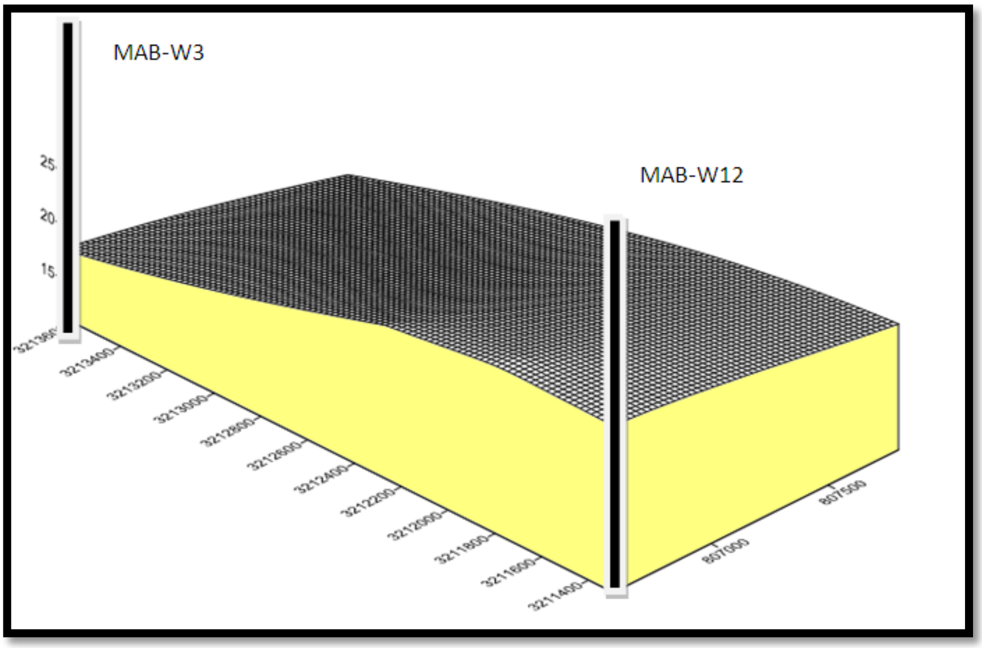


Figure 4.21 Cross sectional view of MABW12-MABW3

Governing eqautions

Ground water flows with respect to head gradients according to Darcy's law and continuity equation in the x- y axis :

$$u_x = -\frac{k}{\eta}\frac{\partial P}{\partial x} \qquad [4\text{-}1]$$

$$u_y = -\frac{k}{\eta}\frac{\partial P}{\partial y} \qquad [4\text{-}2]$$

$$\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} = 0 \qquad [4\text{-}3]$$

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} = 0 \qquad [4\text{-}4]$$

Where u is the velocity in X –axis , k is the permeability , P the pressure gradient .

The flow of groundwater is directly affected by the K- Zone a cross the study area, with an average Value of 10 E-5 which falls within the range of permeable sand aquifer. The viscosity of contaminated water is taken as 0.001 Kg /m s with Density of 1000 Kg/m3.The geometry can be imported in FEMLAB to simulate the velocity and concentration profile in three dimensions.

Boundary Conditions

A boundary condition is a constraint applied on the groundwater model that characterizes the relationship between the aquifer being modeled and the environment outside the aquifer. Boundary condition has been prepared on the field information collected. The two dimensional model can be introduced as per two wells scenario as per figures **(**Figure 4-22**,** Figure 4-22 and Figure 4-22**).**

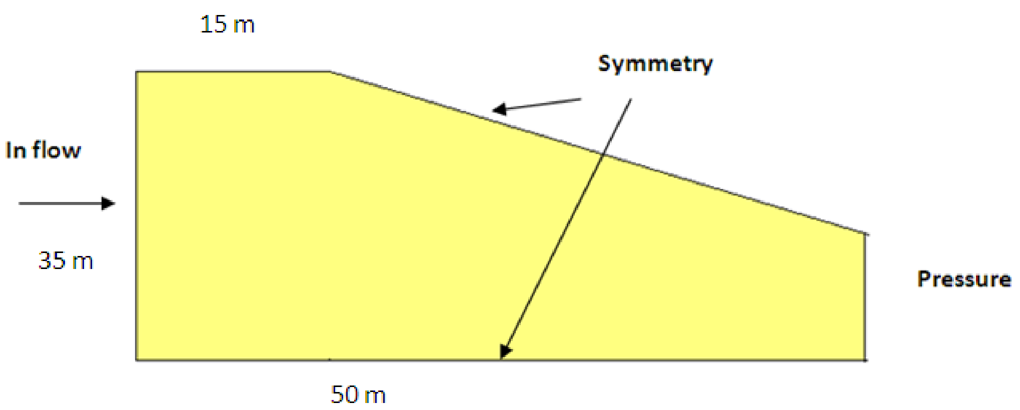


Figure 4.22 Geometry of MABW7-MABW3

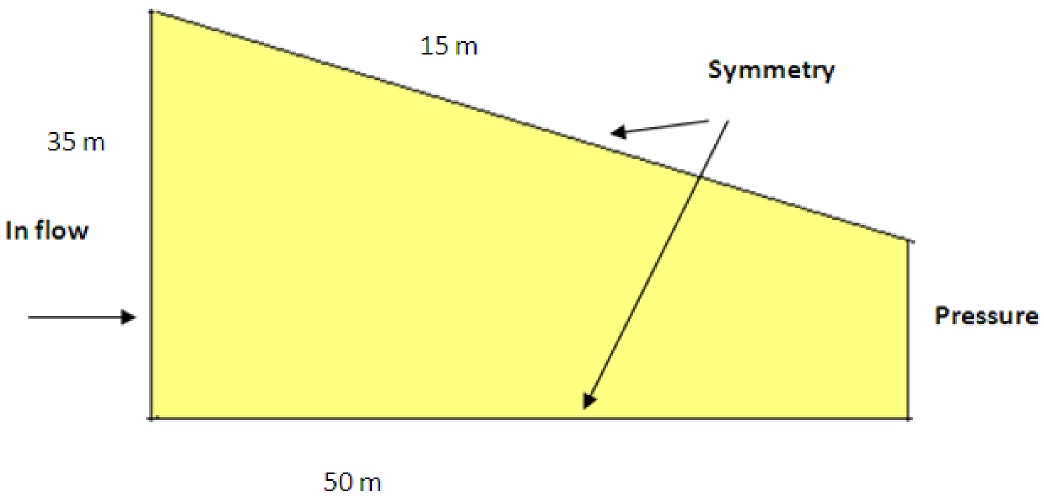


Figure 4.23 Geometry of MABW7-MABW6

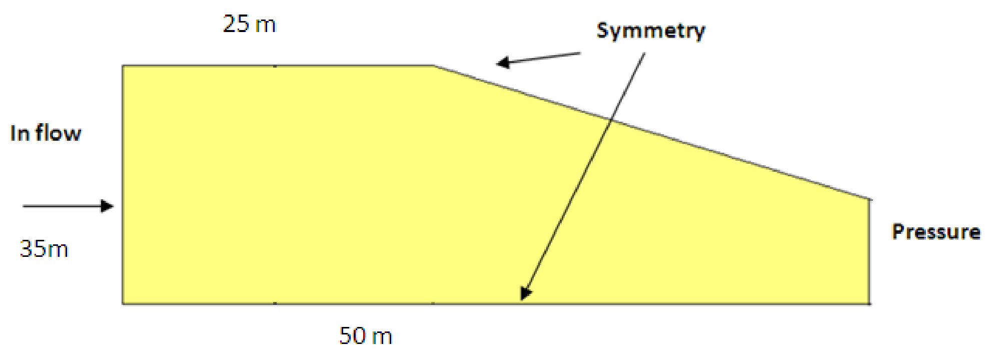


Figure 4.24Geometry of MABW12-MABW3

Conceptually, the model was set up so that water enters the system by lateral flow, and a small amount of infiltration from precipitation that will be distributed across the study area as net charge which is not significant.

In the absence of infiltration test for the Ahamdy area, an estimate of the recharge boundary condition had to be made. Annual estimated recharge at Kuwait Airport is presented in Table 4-5.

Table 4-5. Recharge Estimate for Kuwait Airport

Recharge (mm / year)	**Return Period (years)**
1.2	2
16.8	5
31.4	10
47.6	20
86.5	100

Table 4-4 shows that yearly recharge value of 1.2 mm can be expected every 2 year while a recharge of 86.5 mm can be expected every 100 year. Taking into account the values of infiltration rate assessed by Martin and Normand,(1992) conservative estimate of 10 mm/yr recharge was assigned to the model.

Calibration of Hydraulic Parameters

Hydraulic conductivity was defined based on the conceptual model. since hydraulic data did not exist at the onset of the work, initial values were adopted from Um Al Aish and Al Rawdhatain Area(North of Kuwait).Accordingly , initial hydraulic conductivity (K) was assigned at 8 E-4 m/s. Also the recharge was assumed to be homogenous during the year.

To address the problem, manual calibration was carried out taking into consideration the scientific literature by varying the values of k until a good match between simulation and measurement was attained. It was concluded that the hydraulic conductivity values ranging between 5 E-6 m/s and 8E-4 m/s.

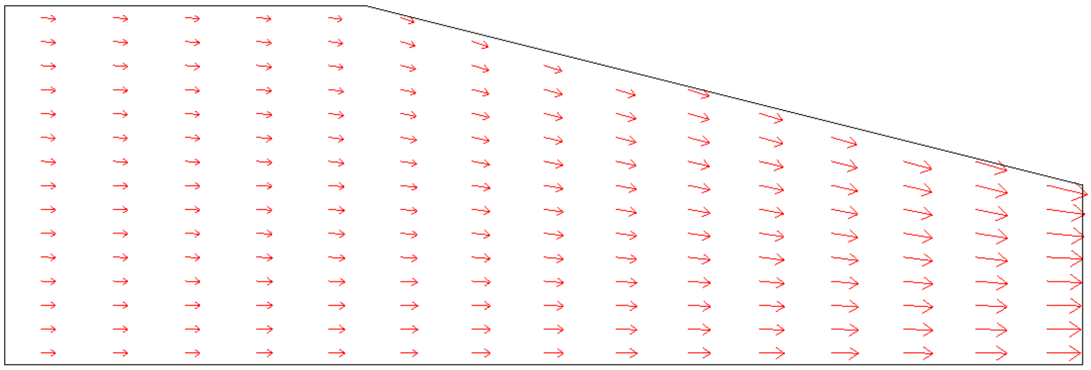


Figure.4.25. MABW12-MABW3 Simulation

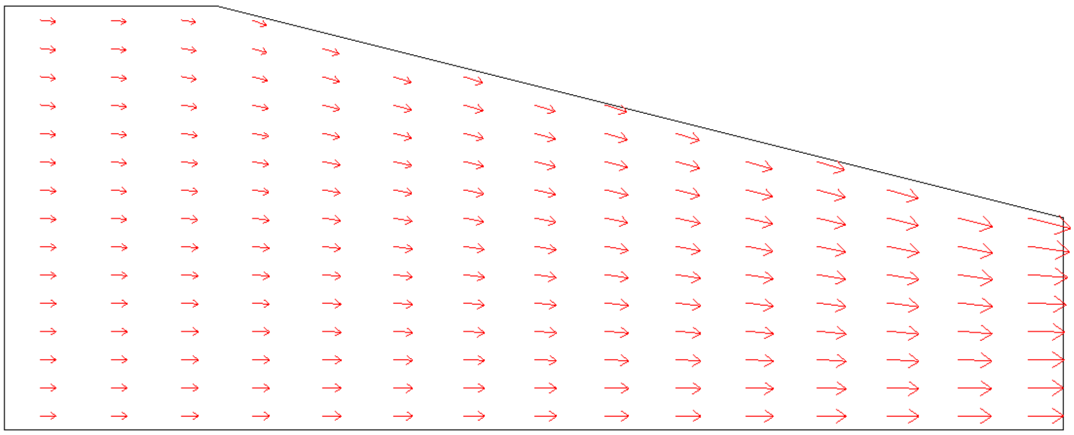


Figure.4.26. MABW7-MABW3 Simulation

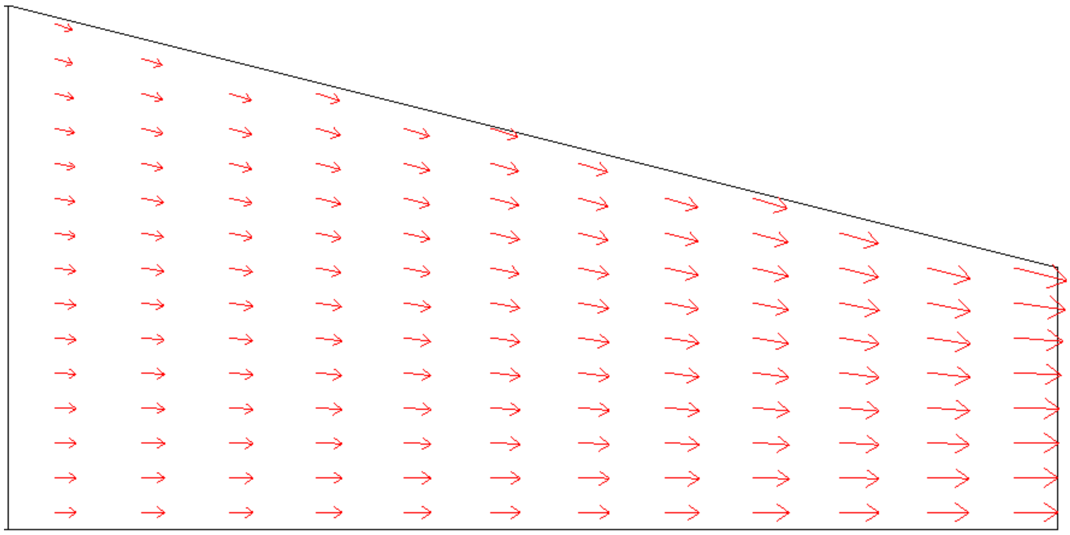


Figure.4.27 MABW7-MABW6 Simulation

The simulation results as presented in (Figure.4-12,Figure.4-12,Figure.4-12) shows that the total water flux flow vary from 0.55 to 1.26 for 1m X 1m and 5.24 for 10m X 10m a day ,12.56 for 25m X 25m and 24.56 for 50m X 50m dimension. Therefore, the water balance calculation indicated that the approximate volumes entering the system shown in figure.4-15 to the west and from the surface recharge were respectively 14,100 and 1,800 cubic meter per day. On the other hand the total volume of water exiting the system from eastern boundary (sea side) is approximately 15,100 Cubic meter per day table 4-5. Accordingly there is less than 0.1% discrepancy between the volume of inflowing and out flowing water. This means that the entire volume of water is accounted for, and no mass losses have occurred, thus giving additional credibility to the computational process

Table.4-5. Water Balance Calculation

Out	**In**	**Water Balance**
15,100	14,100	Constant flow m3/d
	1,800	Recharge

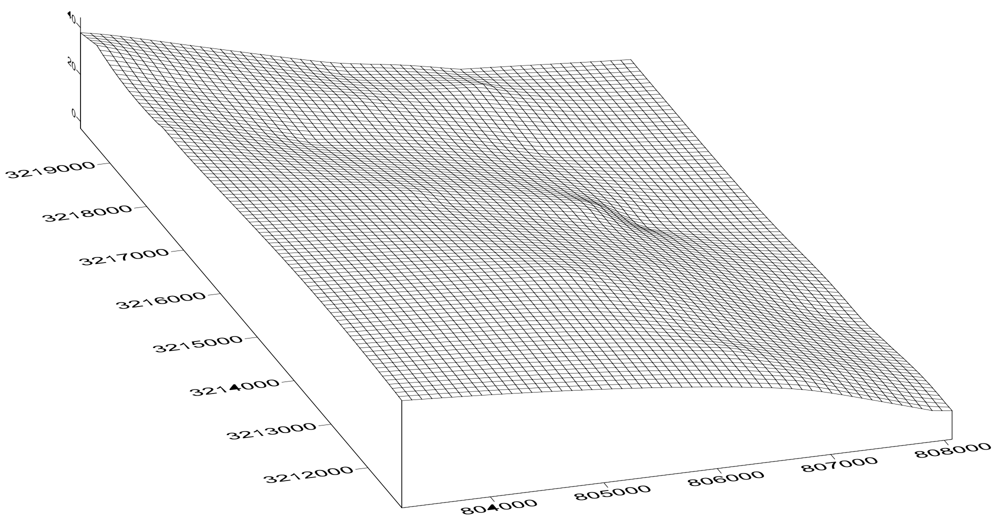


Figure.4.28. Study area model

Well head Calculation

It was concluded from the previous simulation results that the head gradient was varied from 3-4 meter from west to east. Thus, to present a good verification to the model a well –to-well comparison gave a local representation of the hydraulic conductivity which is being calculated before. The comparison results shown in table.4-6.

Table4-6. Comparison between Water head Calc Vs Obs

Well No	East	North	**Obs.**	**Calc.**	**Calc-Obs**
MAA-1	806558	3219750	0.3	2	1.7
MAA-2	806707	3219234	1.5	2	0.5
MAA-3	805834	3219593	7.4	8	0.6
MAA-4	806648	3217726	1.1	2	0.9
MAA-5	805991	3219797	6.44	7.5	1.05
MAA-6	805467	3219559	9.43	10	0.67
MAA-7	806572	3219179	5.5	6.5	1
MAA-8	806409	3219034	6.23	7	0.77
MAA-9	805300	3218713	11.58	9	-2.42
MAA-10	803723	3218766	17.9	20	2.1
MAA-11	803221	3219359	26.7	27	0.3
MAA-12	804560	3217714	13.42	14	0.58
MAA-13	803259	3217609	25.78	28	2.22
MAA-14	803256	3217598	26.06	28	1.94
SHU-1	802064	3217915	NA	NA	NA
SHU-2	807484	3215534	NA	NA	NA
SHU-3	806928	3215521	4.65	5	0.35
SHU-4	806907	3215800	NA	NA	NA
SHU-5	806862	3216014	NA	NA	NA

SHU-6	806809	3216035	5.6	6.	0.4
SHU-7	806577	3216015	8.82	10	-0.69
SHU-8	806439	3215996	10.3	10	1.7
SHU-9	806402	3215731	11.5	12	0.5
SHU-10	805986	3215496	14.49	16	0.51
SHU-11	805176	3215730	17.36	18	0.54
SHU-12	804918	3215952	14.35	16	0.65
SHU-13	806190	3215995	NA	NA	NA
SHU-14	806375	3215990	NA	NA	NA
MA**B-1**	806583	3212272	15.96	16	0.04
MA**B-2**	806667	3211787	15.06	16	0.94
MA**B-3**	806805	3211295	13.63	16	2.37
MA**B-4**	807897	3211079	5.8	8	2.2
MA**B-5**	807320	3211776	11.35	12	0.65
MA**B-6**	807653	3212328	4.79	7	2.21
MA**B-7**	808069	3212677	2.39	4	1.61
MA**B-8**	807908	3213323	2.61	3	0.39
MA**B-9**	807802	3213647	2.58	3	0.42
MA**B-10**	808069	3212677	2.74	3	0.26
MA**B-11**	807908	3213323	4.14	6	1.86
MA**B-12**	807802	3213647	4.16	6	1.84
MA**B-13**	807048	3214103	5.9	6	0.1
MA**B-14**	806495	3214226	7.61	8	0.39
MA**B-15**	805519	3213667	13.48	14	0.52
MA**B-16**	806148	3213217	10.41	12	1.59
MA**B-17**	805858	3213226	15.85	16	0.15
MA**B-18**	806406	3211918	16.49	18	1.51

4.6 Conclusion

The data were compared with the Kuwait EPA regulations for MCL for industrial wastewater to be discharged to the sea. The TPH values from W12 and Wl4 (Mina Abdullah refinery) and W8 (Mina Shuaiba refinery) exceeded the maximum allowed limit. The phenol concentration exceeded the limit at W10 (Mina Abdullah refinery) and W8 (Mina Shuaiba refinery). In some of the wells, high levels (exceeding the maximum limit) of coliform bacteria were detected. The high levels of solutes in the groundwater at the three KNPC oil refineries suggest that the water should be treated to either reduce or eliminate contaminants from the groundwater before it is discharged to the sea .

pH, EC, and TDS. The pH analysis of the groundwater samples from the Mina Al-Ahmadi refinery indicated a slightly acidic environment (ranging from 6.28 - 6.99 with an average of 6.73), which might be due to the presence of organic acids in the water .

The EC of the water ranged from 11,600 ts/cm to 35,868 Ls/cm with an average value of 23,352 s/cm. The salinity of the groundwater was expressed as TDS and ranged from 7372 mg/l to 23935 mg/l with an average of 15667.0 mg/l, indicating the presence of brackish (W2, W12, and W13) and saline water (the remaining wells) in the area. The pH values of the groundwater samples from the Al-Shuaiba refinery indicated a slightly acidic environment (ranging from 6.16 to 7.55 with an average of 6.74), which might be due to the presence of organic acids in the water .

The EC of the water ranged between 2258 µs/ cm and 35,200 µs/ cm with an average value of 14,585 µs/ cm. The salinity of the groundwater was expressed as TDS and ranged between 1242 mg/l and 27421 mg/l with an average of 11028 mg/l.

Wells W4, W6, W7, W8, and W9 encountered brackish water. The lower salinity values observed for these wells suggest freshwater recharge to the aquifer.

Major Anion/Cations and Trace Elements. The majority of the anion and cation data were obtained from wells W1, W2, W3, and W4. The calculated cation-anion balance errors fell within the accepted range ± 10.The trace elements were analysed in wells W2, W3, W4, W5, and W8 only because they were located near possible sources of trace element contamination. The results indicated that boron was present (0.62 mg/l - 9.50 mg/l, with an average of 3.28 mg/l), which exceeded the Kuwait EPA (Environment Public Authority) limit (0.75 mg/l) for discharge to the sea. The highest concentration was found in well W8. A low concentration of molybdenum was found in W4, W5, and W8, and a small amount of zinc was detected in W5. The concentrations were determined for well W6 and W12 only because no spent catalysts were stored in the Al-Shuaiba refinery. These two wells were selected for trace element analysis because they were located on the west and east perimeters of the refinery.

TOC, TPH, and Phenol. The TOC content of the groundwater samples from the Mina Al-Ahmadi area ranged between 0.90 mg/l and 34.44 mg/l with an average of 3.80 mg/l. Relatively high values of TOC were found in the groundwater from wells W7 and W9 as a result of the surface and subsurface hydrocarbon contamination .

Low levels of TPH (between 0.15 mg/l and 7.74 mg/l with an average of 1.18 mg/l) were detected in most wells, except for wells W7, W9, and W12. The results also indicated variations in the TPH content within the aquifer, which might be related to variations in the content of the permeable materials within the aquifer. Phenol compounds were detected in W1, W2, W3, W5, W6, and W7 only, the concentration of which ranged from 0.01 mg/l to 0.24 mg/l with an average value of 0.066 mg/l. High concentrations of TOC were observed in wells W6, W7, W8, and W12. Surface and subsurface hydrocarbon contamination was observed during site visits in groundwater wells W7 and W8, which could be associated with calcareous sandy silt formation. The source of contamination could be the APi, Su 32-01, or leakage from the steel pipes that discharge contaminated water from the storage tanks to the API

CHAPTER 5
FUTURE WORK

5.0 FUTURE WORK

The results of this study predict the level of pollution in Ahamdy Area by showing the concentrations profile of some hydrocarbons with respect to different infiltration rates and permeability . On the other hand the importance of this study will be extended to set the recommendation for the new projects which is coming in the next few years in the Ahamdy Area from environmental point of view specially the New Refinery Project in the Al-Zour region (South part of Ahamdy Area)

CHAPTER 6

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CHAPTER 7

APPENDIX

MAA LABORATORY RESULTS (NOV 2012)

Well No	pH	EC (us/cm)	ORP (mv)	TDS (mg/l)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	HCO3 (mg/l)	SO4 (mg/l)	Cl (mg/l)	NO3 (mg/l)	TOC (mg/l)	TPH (mg/l)	Phenol (mg/l)
W1	6.93	29078	31.8	17447	4600	220	880	361	190	4000	6660	47.5	1.16	0.16	0.03
W2	6.88	28978	30.9	17387	4600	220	876	358	190	4000	6660	44.5	2.86	0.31	0.04
W3	6.84	28813	31.4	17288	4600	220	870	355	190	3900	6640	42	2.28	20.22	0.07
W4	6.83	28760	31.1	17256	4600	220	870	350	190	4000	6640	42	1.28	0.19	0.01
W5	6.78	28730	31.3	17238	4600	220	870	354	190	3900	6640	42	3.13	0.66	0.05
W6	6.77	28873	32.4	17324	4600	220	880	358	190	4000	6660	44.5	6.22	0.63	0.06
W7	7.78	29043	32	17426	4600	220	680	361	210	4000	6680	47.5	8	1.88	0.08
W8	6.8	13403	27.3	7372	1300	70	684	220	212	2800	2000	5.3	1.26	0.26	0.01
W9	6.83	13474	29.2	7411	1320	73	860	221	220	2800	2050	5.5	5.45	3.67	0.01
W10	6.93	25953	30.6	15572	4200	200	865	220	226	3600	5960	17.5	1.17	0.17	0.01
W11	6.97	26018	26.6	15611	4200	210	940	226	224	3600	6000	18	1.35	0.47	0.01
W12	6.81	27556	29.6	16534	4300	220	770	224	360	3700	6200	17.6	34.44	5.46	0.01
W13	6.85	27600	40.7	17915	4550	213	765	510	350	2900	7700	7.2	4.19	1.73	0.01
W14	6.77	25000	35.9	16583	4500	213	764	508	355	2800	7600	6	0.9	0.21	0.01

MAB LABORATORY RESULTS (NOV 2012)

Well No	pH	EC (us/cm)	ORP (mv)	TDS (mg/l)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	HCO3 (mg/l)	SO4 (mg/l)	Cl (mg/l)	NO3 (mg/l)	TOC (mg/l)	TPH (mg/l)	Phenol (mg/l)
W1	6.48	6483	73	3890	790	72	370	139	95	1700	750	50	1.81	0.27	0.01
W2	6.44	28876	-276	21657	5200	346	1312	444	205	3600	9800	5	1.05	0.18	0
W3	6.54	25310	-50	18983	4700	340	1400	650	184	3000	8650	5.7	1.14	0.22	0.03
W4	6.43	6398	-81	3839	1050	76	110	28	117	2000	375	34	4.96	0.34	0.01
W5	6.8	9901	-38	5941	1690	80	268	68	95	1700	1850	176	1.99	0.38	0.01
W6	6.8	9516	-39	5710	1130	36	596	149	172	2000	1550	26.4	9.6	2.6	0.01
W7	7.53	17915	NA	11645	2510	130	792	225	155	3200	4080	32.6	3.66	0.3	0.12
W8	6.91	22104	-415	14368	3300	186	424	388	235	2900	5600	6.6	2.95	0.37	0.01
W9	6.44	20778	-155	12467	3150	176	496	296	675	2700	4950	7.9	6.5	0.75	0.01
W10	6.67	12891	-374	7735	1750	100	304	10	1240	150	3000	12	51.4	9.16	2.22
W11	6.5	23860	-30	14316	3900	190	924	266	505	3200	5200	8	15.36	6.48	0.01
W12	6.88	28906	-4	18789	4600	220	1045	430	164	3800	7700	5.2	10.37	3.16	0.24
W13	6.85	30561	-29	18337	4600	220	1040	425	165	3700	7700	5.7	1.03	0.16	0.01
W14	6.91	19785	-49	11871	3000	180	560	98	110	3000	4600	13.2	24.48	9.35	0.14
W15	6.98	29703	-12	17822	4600	225	1090	400	185	4800	7500	6.6	1.5	0.21	0.03
W16	6.82	23598	-88	14159	2800	180	720	269	230	4500	3200	360	5.81	1.19	0.21
W17	6.63	31923	-114	19154	4800	341	975	436	190	3600	8600	5.7	1.15	0.22	0.13
W18	6.98	11910	-55	9163	2200	150	512	90	127	3200	2580	13.6	0.55	0.17	0.01

SHU LABORATORY RESULTS (NOV 2012)

Well No	pH	EC (us/cm)	ORP (mv)	TDS (mg/l)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	HCO3 (mg/l)	SO4 (mg/l)	Cl (mg/l)	NO3 (mg/l)	TOC (mg/l)	TPH (mg/l)	Phenol (mg/l)
W1	6.9	7779	-75	4968	800	60	532	67	248	1800	1100	0.4	3.87	0.22	0
W2	7.55	5290	-65	4189	530	24	363	38.6	370	1000	55	12.8	1.07	0.17	0
W3	6.55	5290	-68	3834	465	24	449	56.2	410	800	37	13.6	3.37	0.17	0
W4	7.2	8960	-110	7133	1580	74	500	103.8	372	2700	170	8.4	0.91	0.19	0
W5	7.44	4463	-125	3024	190	22	86	19	196	200	40	5.7	4.37	0.32	0
W6	6.86	3886	-62	2745	94	18	56	12.2	35	160	70	19.8	203	2.51	0
W7	6.27	3861	-106	2931	96	18	50	17.1	30	160	60	24.6	271	2.86	0
W8	6.28	4720	-105	4546	700	50	494	36.6	230	800	700	6.2	24.93	8.38	0.01
W9	6.22	14410	-44	12821	2900	190	608	178	195	4000	3760	41.8	207	61.5	5.32
W10	6.25	30200	-32	21067	4900	360	984	506	189	4800	8480	45.3	148	31.73	3.28
W11	6.44	27600	-42	20448	6650	350	952	449	219	5000	7980	46.6	16.8	2.74	0
W12	6.25	34200	-245	25995	6660	460	1322	495	238	4100	11980	0	7.7	0.32	0.09
W13	6.41	34600	-240	26849	6650	460	1332	547	228	3900	12060	0.5	0.91	0.19	0
W14	6.16	112280	-39	26536	2055	41	628	37	500	5900	860	11	315	2.42	0

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